The Influence of Management on the Vegetation and Carbon Fluxes of Blanket Bog

A thesis submitted for the degree of Doctor of Philosophy
University of Edinburgh
Alan Gray March 2006

Declaration

This thesis was written by myself and represents the results of my own work, except where stated otherwise, and has not been submitted in an application for any other degree.

Alan Gray, March 2006

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Abstract

This thesis presents evidence of the impact of anthropogenic management on the blanket bog ecosystem. The effects of management on carbon fluxes and vegetation through control of grazing and burning for blanket peats in the UK are explored and calculations of tentative climate warming potential of sample sites in the Sutherland and Caithness peatlands are presented. An examination through semi-quantitative literature review and the analysis of published field work data, of the relationship between the management of blanket bog and gaseous carbon fluxes in the UK, is presented.

The geographical distribution of peatlands and blanket bog in the UK and the management actions that influence them are summarized. Previous work in relation to management on blanket bog is reviewed and some hypothetical ways in which management may affect carbon fluxes are discussed. The main published works in the UK on carbon flux from peatland systems is reviewed, including fluxes to river systems in the form of dissolved organic carbon.

A semi-quantitative synthesis of the published gaseous carbon fluxes in the UK reveals gaps in research. Mean methane emission is approximately 0.029 μmol CH_4 m^{-2} s^{-1}, but there is no reliable estimate for net gaseous flux rates of carbon dioxide from UK blanket peats and both winter fluxes and the impact of peatland management practices have been understudied.

The links between vegetation and management are analyzed through vegetation survey of blanket bog areas in the Caithness and Sutherland peatlands at the RSPB Forsinard Reserve and a long-term burning and grazing split plot experiment in the Moor House-Upper Teesdale National Nature Reserve. Vegetation structure as well as species composition was shown to be affected by management. The National Vegetation Classification method was insensitive to management treatments and may be of limited use for indicating management practices in the wider landscape for peatland ecosystems in the UK.

Key climatic controls of gaseous carbon fluxes at the site scale were photosynthetically active radiation for CO_2 in the light, soil temperature for CO_2 in the dark and soil temperature for CH_4 flux. There were some departures from theoretical predictors of gaseous fluxes that may have links to site management.

The influence of management on the gaseous fluxes from the blanket bogs of the RSPB reserve at Forsinard is explored through the use of general linear models and regression analyses. A tentative carbon balance for certain sites within the reserve over the period of a year indicates that differences between sites that may be attributed to management. Heavily damaged sites appear to fix less and respire more CO_2. Fire may lead to initial increase in CH_4 emissions. However, the effect of management in terms of drainage may not always be immediately apparent. Further temporal and spatial resolution of the effects of peatland management on carbon fluxes is required. Proposal for further research include the calibration of indicators of carbon fluxes in UK peatlands.

Preface

The majority of PhD research has its problems. I, like many other students before, have had my fair share of 'ordinary' problems such as, leaking flux chambers leading to months of redesign and testing, faulty datalogger's that take 3 months to fix, experiments that take weeks to set up then don't work, and even weather that appears to conspire to disrupt field work. These though dreadful at the time fade once a sufficient period has passed, or writing up commences, only to be recalled during discussions with friends over several pints of beer.

However I had two rather more serious problems, which help to put this thesis in context. The first of these happened on the 13th (I'm not making this up honest!) of May 2004 and is illustrated below. No I did not do my field work in a war zone, but yes this was my Land Rover. The fire, caused by a faulty starter motor, also set the adjacent Forest on fire and without the timely intervention of James Plowman would have been far more serious. This resulted in a brief period where communication with other people was difficult due to my propensity for blasphemy during normal conversation, but I did recover. More importantly the loss of equipment put field work back 2 months while the equipment and the vehicle were replaced (which is another long story involving Land Rovers).

The second problem happened at the tail end of 2004 and is more commonplace, hard disk failure. This is bad enough but was compounded by all of my back up disks being corrupted and resulted in the loss of 6 months work. I was saved from complete disaster by the timely intervention of the RSPB who together with the Scottish Executive and SNH funded my research for an extra year in 2005.
So remember;

There is no such thing as having too many back ups,

and

be wary when buying Land Rovers.

There so much I wanted to say here but in the end the photograph says it all!!

Thesis Aim and Layout

Thesis Aim

The general aim of this thesis is to examine the influence of management practices on the gaseous carbon fluxes of blanket bog.

Thesis Layout

The layout of this thesis is generally in the style of scientific papers, although this differs in Chapters 1, 6, and 7. However in an attempt to avoid unnecessary repetition, some introductions are shorter than normal and where methods have already been detailed subsequent chapters will only refer to the previous chapter where the methods are already stated. Versions of Chapters 1, 2 and 5 appeared as unpublished reports for the Scottish Executive and the RSPB in 2005.

Chapter 1: Introduction.

This summarizes the geographical distribution of peatlands and blanket bog in the UK and the management actions that are carried out on them. Previous work in relation to management on blanket bog is reviewed and some hypothetical ways in which management may affect carbon fluxes is discussed. A review of some of the main work in the UK on carbon flux from peatland systems and from peatland river systems in the form of dissolved organic carbon is also included.

Chapter 2: Peatland gaseous carbon fluxes and land management: searching for a paradigm.

The main work on gaseous carbon fluxes in the UK is semi-quantitatively reviewed and an attempt to synthesize previous work to identify areas of future research is made.

Chapter 3: Blanket Bog Site Characteristics and the Role of Management

The vegetation of blanket bog areas belonging to the Caithness and Sutherland Peatlands within the RSPB Reserve at Forsinard are described and analysed in relation to management and site specific factors. A vegetation survey of a split plot burning and grazing experiment is also analysed to determine how this type of management affects blanket bog vegetation.

Chapter 4: Environmental relationships to the gaseous carbon fluxes of blanket bog.
Gaseous flux data from the blanket bogs of the RSPB reserve at Forsinard are used to identify the main environmental climatic controls through the use of regression models.

Chapter 5: Does management influence the gaseous carbon fluxes of blanket bog?
The influence of management on the gaseous fluxes from the blanket bogs of the RSPB reserve at Forsinard is explored through the use of General Linear Models. Regression models are also used to explore a tentative carbon balance for certain sites within the reserve over the period of a year.

Chapter 6: Discussion.
This discussion brings the previous chapters together and discusses what the thesis means as a whole.

Chapter 7: Conclusions and Further Work.
Summary concluding points are made from all chapters and suggestions for further research are made.

Table of Contents **Page**

Contents		Page

Contents **Page**

Chapter 2 Peatland gaseous carbon fluxes and land management: searching for a paradigm. 63

Contents		Page

Contents		**Page**

Contents **Page**

Table of Figures **Page**

Chapter 1

Chapter 2

Chapter 3

Chapter 4

List of Tables

Page

Chapter 1

Chapter 2

Chapter 3

Chapter 4

Chapter 5

Appendices

Chapter 1: Blanket Bog Ecosystem Carbon Fluxes and Management

This chapter introduces the blanket bog as an ecosystem and places it within a UK and Scottish perspective as well as examining factors that may be important to climate change and carbon balances. Examination is made of not only ecologically important but also political factors that may have an impact upon the management and carbon dynamics of blanket bog in the UK. This chapter has written contributions by Neil Wilkie concerning the Peatland Management Scheme, LIFE Nature and Heritage Lottery sections, Mike Wood for the Scottish Forestry Grants Scheme, and Mandy Gloyer for Agri-environment Schemes and Land Management Contracts.

1.1 Introduction

There is a prevailing awareness that changes in climate at the global scale are a direct consequence of human activity and are predicted to persist for decades even under the most optimistic scenarios (Hulme et al., 2002; Hulme, 2005; King, 2005). That these changes will have associated effects on biodiversity is also likely (Hulme, 2005; King, 2005). The ability to address losses in biodiversity and global climate change requires the scientific understanding of biogeochemical cycles and how the processes such as disturbance affect biotic survival. Untangling the interactions of human activity and their effects on biological processes are some of the most earnest and challenging research questions faced by ecologists, spanning local, national and global scales.

Global climatic change is expected through the enhancement of the earth's natural greenhouse effect by the rising concentrations of certain atmospheric greenhouse gases. The natural greenhouse effect arises from absorption of outgoing infrared radiation by greenhouse gases which is then emitted in all directions including to the earth's surface keeping the surface at a higher temperature (~14 °C) than would be the case in the absence of this effect (IPCC, 2001). Carbon dioxide (CO_2) is a powerful greenhouse gas and may contribute 60 % of observed global warming effect (Grace, 2004). The evidence that concentrations of CO_2 have been rising in the atmosphere is unequivocal (IPCC, 2001), Figure 1.2 illustrates the rising concentrations recorded at Mauna Loa from 1958 until 2004.

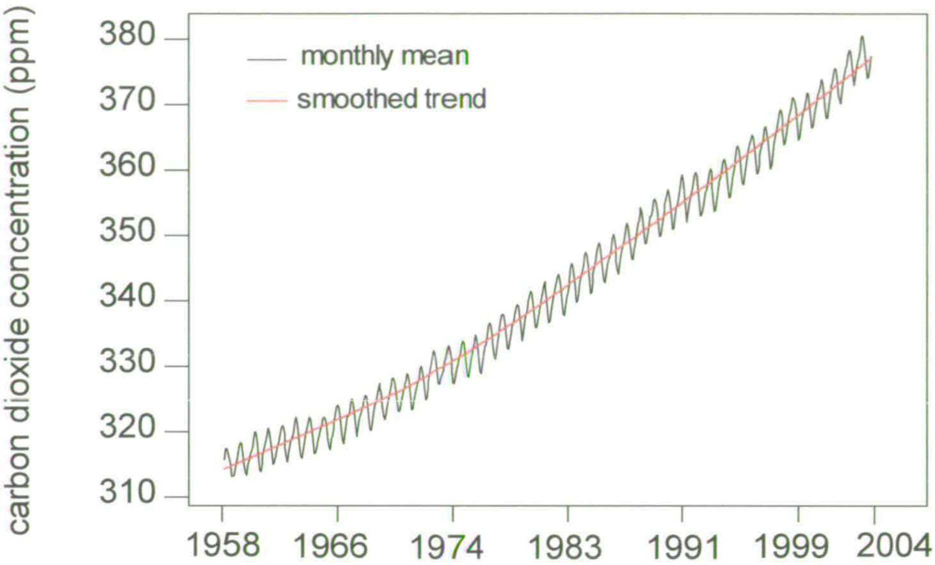

Figure 1.2: Rising concentrations of CO_2 recorded at Mauna Loa (Keeling & Whorf, 2005).

The observed rising concentration is not the only perceptible phenomenon shown by Figure 1.2, there is also an important seasonal drawdown due to northern hemisphere vegetation photosynthesis emphasising the importance of the biotic factors in carbon cycle. The rise of CO_2 in the atmosphere correlates with increases in fossil fuel consumption due to industrial activity (IPCC, 2001). There are several other gases that contribute to the overall greenhouse effect these include direct greenhouse gases, such as, methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6) and indirect greenhouse gases, nitrogen oxides (NO_x, as NO_2) carbon monoxide (CO) non-methane volatile organic compounds (NMVOC) and sulphur dioxide (SO_2) (IPCC, 2001; Baggott et al., 2004).

Peatland ecosystems exchange both CO_2 and CH_4 but also represent a large store of carbon within the peat and host a distinctive assemblage of species, which, if lost, would decrease global biodiversity and potentially increase atmospheric carbon.

Activities carried out on peatland ecosystems that may bring about these effects include drainage, agricultural improvement, burning, the effects of large herbivores, peat extraction and climate change. More than 85% of all peatlands are located in the northern temperate, boreal and arctic zones. These ecosystems (including tundra and boreal forests) are estimated to store 1.2 x 10^{18} g C (O'Neill, 2000). Bogs and fens alone account for approximately 3.0 – 4.6 x 10^{17} g C within an area of approximately 350 million hectares (O'Neill, 2000 and references therein). This may be equivalent to the total amount of carbon present in the atmosphere today (Clymo et al., 1998). With the uncertainties of ecosystem response to global climate change, the importance of conserving this carbon store cannot be overstated.

The term peatland covers a wide range of peat-forming vegetation including tundra, boreal forests, fens and bogs (O'Neill, 2000), although the most important peatland habitat in the UK is blanket bog. Blanket bog can be defined as areas of semi-natural vegetation over-lying peat of at least 0.5 m depth and forming a blanket over moderately sloping ground (NCC, 1990). It is regarded as the most extensive semi-natural land habitat in the UK covering at least 1.4 million hectares (Lindsay, 1995). The Flow Country in Sutherland and Caithness, in the north of Scotland, may be the largest area of continuous blanket bog in the World (Lindsay et al., 1988). The UK holds 10-15% of the total world area of this habitat (Lindsay, 1995) and, of this, Scotland holds over 1 million hectares; considering the UK is only approximately 0.16% of the global land mass this emphasises the importance of this habitat. The importance of the peat carbon store in the UK is demonstrated in Figure 1.1 whereby the majority of soil carbon can be seen to be located within Scotland and the majority of this constitutes blanket-peat. It is estimated that peatlands with a depth of over 45 cm contain 50% of all soil carbon and up to 40 times that which is contained within terrestrial vegetation in the UK (Cannell & Milne, 1995; Milne & Brown, 1997).

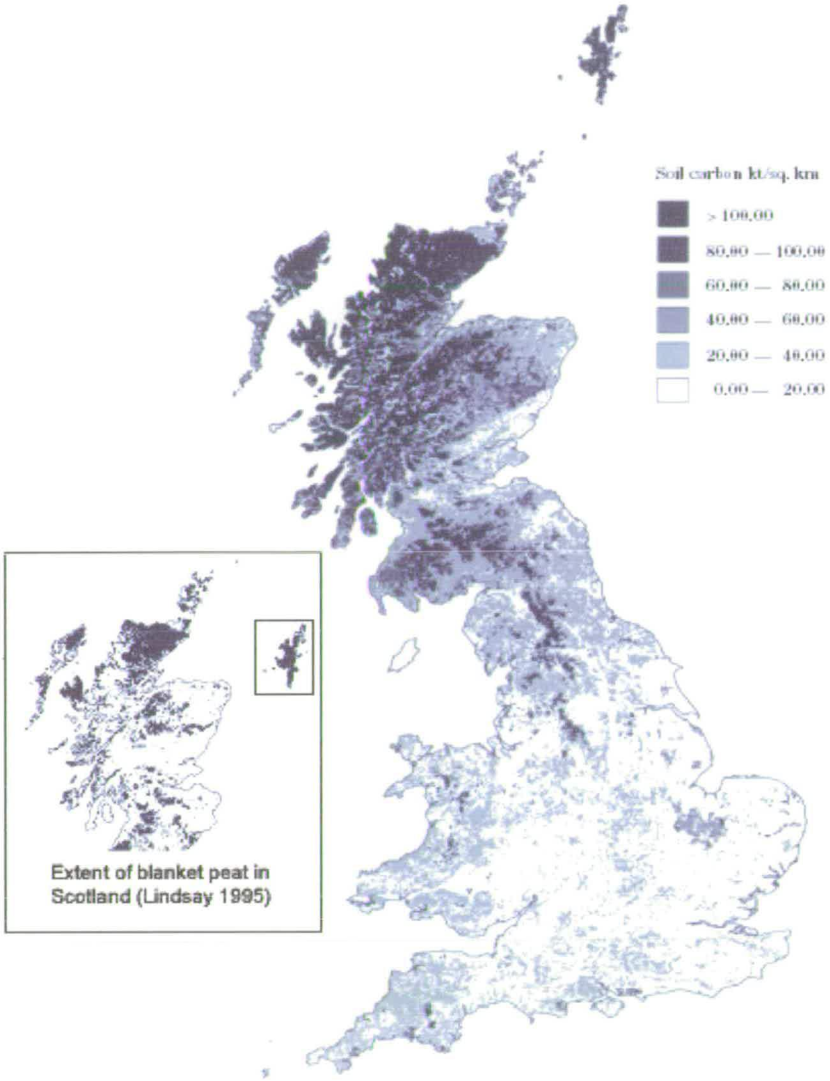

Figure 1.2: The soil carbon content (kt km^{-2}) of the United Kingdom (Milne & Brown, 1997) with the extent of blanket bog in Scotland (inset) defined as land with a depth of peat over 0.5 m (Lindsay, 1995).

The development of blanket bog is a function of past and present environmental factors (e.g. climate, geology, geomorphology) and of the nature, intensity and history of human impact (Steiner, 1997). Bog ecosystems can be divided into two layers, the active growing layer (the acrotelm) and the layer of accumulated peat (the catotelm) (Ingram, 1978). Active blanket bog is an unbalanced system where plant production in the acrotelm exceeds the combined losses from decomposition of organic material and leaching of organic and inorganic carbon compounds (Vitt, 2000). Gaseous carbon exchanges with the atmosphere are dominated by the exchange of carbon dioxide (CO_2) and methane (CH_4). The net balance between the processes of photosynthesis and respiration determine the net gaseous CO_2 exchange and establish whether the peatland is a sink or source of CO_2. Gaseous exchange of CH_4 is dominated by the process of methanogenesis in the catotelm emitting CH_4 to the atmosphere. Oxidation of CH_4 termed methanotrophy also occurs under aerobic conditions in the acrotelm but the balance between these two processes is generally in favour of methanogenesis, i.e. peatlands are a source of CH_4. Both methanogenesis and methanotrophy are carried out by micro-organisms, generally bacteria. Other exchanges of carbon include the export of particulate and dissolved carbon into river systems and losses to the atmosphere through fire.

The relative importance of these processes to the total carbon balance varies spatially and temporally. The carbon balance of UK blanket peat is a major factor in assessing UK's greenhouse gas emissions (Milne & Brown, 1997). The majority of the blanket bog resource in the UK is subjected to management by agricultural drainage (moor grips), grazing, burning and forestry, but with the exception of forestry (Hargreaves et al., 2003), the variability of carbon dynamics under different types of management has yet to be quantified in the UK.

The Scottish Biodiversity Strategy recognises the importance of peatlands in relation to climate change, but active blanket bog is not only important in terms of carbon, it is also classed as a priority habitat under the European Union Habitats Directive (source JNCC). The most important species in conservation terms are within the genus *Sphagnum* and those species associated with them. Active blanket bog is by definition a habitat that is actively accumulating peat, thus sequestering carbon. The conservation of active blanket bogs in the UK is focused on achieving the best representation of hydromorphological types, plant communities, and plant and animal species (JNCC, 1994). However, the active status of bogs in the UK is unknown, therefore, conserving diversity without information on carbon dynamics may not ensure that designated sites are actively sequestering carbon. However, in addition to conserving key species and habitats, it may be possible to manage bogs for carbon sequestration, or more likely the minimisation of carbon losses and the conservation of biodiversity as well as responding to climate change. Currently research is still required for the realisation of the key objectives and targets of UK biodiversity commitments, which include the encouragement of appropriate grazing, burning and other management practices on blanket bog habitats, as well as the restoration of degraded blanket bog to favourable condition by 2015 (Haines-Young et al., 2000).

A better understanding of the impact of policy initiatives (e.g. agri-environment schemes, Scottish Natural Heritage Peatland Management Scheme) on carbon flux of blanket bogs is also required. Such findings are essential to provide information for Government reporting on greenhouse gas emissions, research on ecosystem response to climate change and reviews of Government-funded land-management schemes.

1.2 Geographical Extent of Blanket Bog and Management Relevant to Scotland

The blanket bog resource in the UK is subjected to a variety of different management practices, these include drainage, grazing, burning, ecological restoration and forestry. As the effects of forestry have been investigated elsewhere (Hargreaves et al., 2003) this section will focus mainly on the management practices of drainage, grazing, burning and ecological restoration techniques. This section concentrates mainly on a Scottish perspective as much of the information on geographical extent has had more recent attention for Scotland and the majority of the UK blanket bog resource is in Scotland.

1.2.1 Total blanket bog resource

In a recent review of climate change and organic soils in Scotland Chapman *et al.,* (2001) noted with disappointment that after 50 years of peat survey there is still no definitive estimate for the geographical extent of peatlands in Scotland or the UK (Table 1.1). Part of the difficulties in reaching a reliable estimate for the geographical extent lie in defining the blanket bog habitat. This ultimately depends on the depth of peat chosen which has varied from a depth of over 1 m, to those peats over 0.3 m deep, and on the mapping technique. In Scotland there are extensive areas of vegetation that are essentially bog vegetation but overlie peat that is much shallower than 1 m, for example, the Lammermuir Hills, ignoring this is likely to underestimate the carbon store. Also, if pool systems are not taken into account then estimates would tend to be overestimates; it is unknown whether pool systems are considered in estimates of carbon storage. There are also areas that may once have been mapped as blanket bog but through persistent management practice are now classified as a different habitat e.g. *Calluna* moorland. These may still have a sizeable carbon store, though estimates based on vegetation cover may also underestimate the carbon store. It is also noticeable that the only estimate in Table 1.1 bounded by error estimates is that of the CS 2000 survey, this tends to imply a precision to estimates that is not actually evident. In a recent analysis using NVC survey data and comparing it with the SBBI and LCS 88 estimates, it was found that only 55.5% of the SBBI classifications were in agreement with the NVC whereas 69.7% of the LCS 88 classifications matched the NVC (Andrew Coupar pers comm. 2005). Assuming the NVC surveys themselves were accurate, this may suggest that the LCS 88 data gives a more accurate reflection of the extent of blanket bog (Andrew Coupar pers comm. 2005).

There is also no agreement on the amount of carbon within these soils that is used to calculate the overall storage value. The reasons for this uncertainty are partly due to the uncertainty of extent but also to do with uncertainties surrounding the parameters chosen for calculation (Chapman et al., 2001), for example bulk density; see Chapman et al. (2001) for a fuller discussion. Chapman et al., (2001) conclude that between 2000 and 4500 Mt C is likely to be stored in Scottish peaty soils.

There is therefore a requirement for method refinement to lead to better estimation of carbon content and geographical extent:

- A practical and absolute definition of what should be included in any mapping project including an agreed minimum depth of peat for inclusion.
- A mapping method that not only allows a definitive estimate of geographical extent but also gives an assessment of the errors associated with the estimate.
- A better understanding of the range of depth and bulk density of blanket peats in Scotland.

These aspects are currently under review by the Organic Soils Modelling Project who have used a classification of two broad groups of organic soils (MISR, 1984):

Organic – mineral
Includes all soils with an organic surface horizon < 50 cm thick and an organic carbon content > 14% (25% OM)

Organic
Includes all soils with an organic surface horizon > 50 cm thick (peats) and an organic carbon content > 14% (25% OM). Most peats have organic carbon contents well in excess of this value

Given the uncertainties associated with estimating the total peatland resource and its carbon store, estimates for the extent of management practices on blanket bog will be of similar low precision. Table 1.2 summarises current knowledge of the geographical extent of each of the management practices examined in this thesis. It should be remembered that these are estimates and are likely to be spatially variable and are not mutually exclusive. These estimates in some cases represent a best guess, others such as those from the LCS 88 or SBBI, may appear to have more precision but they are also not bounded by any error or estimation of variation. They should therefore be treated with caution.

Table 1.1: Estimates of the peatland resource of Scotland (Chapman et al., 2001) with additions from The Scottish Blanket Bog Inventory, (SBBI) (Quarmby et al., 1999; Johnson & Morris, 2000c, a, b, d, 2001), Land Cover Scotland 1988 (LCS 88) Andrew Coupar pers comm. 2005, and Countryside Survey 2000 (Haines-Young et al., 2000). [a] Assuming 50% C, [b] probably an underestimate, [c] using the estimated C content of 114 kg C m^{-2}, [d] peat soils > 1 m deep but may include some 0.3 - 0.5 m deep.

Area of peatland kha	**% of Total Area**	**Carbon store Mt C**	**Reference**
821	11	600[a]	(Robertson, 1971)
820	11		(Bather & Miller, 1991)
821	11		(Robertson & Jowsey, 1968)
821	11		(Jowsey, 1973)
765 699 (blanket peat) 66 (basin peat)	9.9		(MISR, 1984)
789 720 (blanket peat) 69 (basin peat)[b]	10.2	1000[a] (approx.)	(Birnie et al., 1991)
1742	22.6	1986[c]	(Cannell et al., 1993)
2625	30.9	16412	(Howard et al., 1995)
2625 2564 (blanket peat) 61 (basin peat)	30.9	4523	(Milne & Brown, 1997)
1332	17.2		(Anon, 1998)
1742	22.6		(Cannell et al., 1999)
1096[d] 1056 (blanket) 40 (other)	14.2		(Patterson & Russell, 2000)

Table 1.1 continued

Area of peatland kha	% of Total Area	Carbon store Mt C	Reference
1927 (blanket bog)			SBBI
660 (peatland as a single feature) 366 (mosaics, peatland as primary component) 1131 (mosaics, peatland as secondary component)			LCS 88
2038 (standard error 168) 2339 upper limit 1754 lower limit			CS 2000

Table 1.2: Estimates for the geographical extent of management on blanket bog in Scotland. [1] SBBI (Quarmby et al., 1999; Johnson & Morris, 2000c, a, b, d, 2001), [2] Land Cover Scotland 1988, * this may be as high as 450,000 ha (W Towers pers. com. 2005, from re-calculation of LCS88 data), [3] JNCC [a] Assumed figure, [b] Includes all peat, not just blanket bog.

Types of Management	Geographical Extent (ha)	% of total area
Total Blanket Bog Resource[1]	1,927,000	100
Grazed	1,927,000[a]	100
Burnt	???	???
Drained	???	???
Eroded[2]	200,000*	10
Used for Peat Extraction[2]	50,000	2.5
Statutory Conservation		
SAC[3]	220,847	11
SPA[3]	261,108[b]	13
SSSI [1]	384,702	20
Ramsar[3]	192,480[b]	10
Under Restoration	11,800	0.6

1.2.2 Geographical Extent of Grazing

It would seem reasonable to assume that the entire area of blanket bog in Scotland has historically (Shaw et al., 1996) and is presently subjected to grazing of one type or another. However what is unclear is the intensity of grazing to which different areas are subjected. Further variability is likely to be introduced from the type of animals grazing on these bogs different animals produce very different effects due to size and pressure of footprint, oral morphology and diet preference. Large herbivores affect peatland systems in several different ways, including defoliation, uprooting, trampling, defecation and urination. Each of these activities will have a different impact on the peatland system.

1.2.3 Geographical Extent of Burning

The extent of burning on blanket peats is not known, but the practice is regionally variable (Hamilton et al., 1997). Although natural fire in Scotland is rare, most blanket peat dominated by either *Calluna vulgaris* or *Molinia caerulea* will be prone to fire, either as a management tool for sheep or grouse, or as accidental or malicious wildfire. Severe ground fires that ignite the peat are rare, but can occur in blanket peat and then cause very considerable damage with loss of carbon to the atmosphere and a complete change in ecosystem function (Maltby et al., 1990).

1.2.4 Geographical Extent of Drainage

The extent of drainage of blanket peats is not known. Stewart and Lance (1983) (Coupar et al., 1997) state that government grants for drainage reached a peak of 80,000 ha per annum in the 1950's and the mean in the 1960-70s was 20,000 ha per annum.

1.2.5 Geographical Extent of Erosion

Based on LCS 88 there are approximately 200,000 ha of eroded blanket bog (Andrew Coupar pers. comm. 2005), but estimates vary and it may be as large as 450,000 ha (W. Towers pers. comm. 2005). The type of erosion will vary from large areas of eroding bog devoid of vegetation to micro-eroded areas from, for example, animal trampling and hagging; the extent of this variability is unknown.

1.2.6 Geographical Extent of Peat Extraction

Based on LCS 88 there are approximately 50,000 ha of bog under cutting or extraction, this is predominantly domestic cutting (Andrew Coupar pers comm. 2005).

1.2.7 Geographical Extent of Conservation

Details on statutory designated sites are held by SNH or JNCC. Extent of sites not under statutory designation but still actively conserved, such as Local Nature Reserves (LNR) or Wildlife Sites has not been collated but will be held by Local Authorities or Wildlife Trusts. Approximately 221,000 ha (11%) has been estimated to be designated Special Area of Conservation (SAC). The extent designated as Special Sites of Scientific Interest (SSSI) is a little larger as some SAC's are a core area within a SSSI or some SSSI's haven't been designated as SAC's. Also, the Lewis Peatlands are an SAC not underpinned by an SSSI designation so this adds to the SAC total but not the SSSI total.

1.2.8 Geographical Extent of Restoration

Approximately 1,800 ha of trees have been removed from blanket peat under the LIFE Peatlands Project in Caithness and Sutherland and this should rise to 2,400 ha by December 2006. Moor grips are currently being blocked over approximately 10,000 ha rising to 15,000 ha by December 2006 again under the LIFE Peatlands Project (Neil Wilkie pers com. 2005). The extent of blanket bog that could be practically restored is considered to be the majority of the total afforested area excluding only those areas under forestry near to the conclusion of the first rotation and those that are severely eroded which are considered beyond recovery (Andrew Coupar pers comm. 2005).

1.3 Carbon Cycle of Blanket Bog

Figure 1.3 illustrates a simplified representation of the carbon cycle of a blanket bog. The main input identified in Figure 1.3 is the uptake of carbon dioxide by the process of photosynthesis. Carbon outputs include carbon dioxide from respiration and aerobic decomposition and methane oxidation, methane from microbial decomposition, and particulate and dissolved organic carbon as well as dissolved inorganic carbon in water that runs off into river systems.

The relative importance of the various components illustrated in Figure 1.3 has been examined in many studies. Emissions of CH_4 accounted for 16% of the net ecosystem exchange of carbon in an oligotrophic boreal pine fen (Alm et al., 1997). However, net ecosystem exchange of CO_2 was estimated to account for 99% of the carbon balance in some circumstances in a patterned boreal peatland (Waddington & Roulet, 2000). The variability of carbon flux is due not only to factors such as the climate and seasonal timing, but also the microhabitat topography, i.e. hummock, lawn or hollow, and importantly the position of the water table. Classical theory suggested that *Sphagnum* growth and peat accumulation in hollows was rapid while hummocks declined (von Post & Sernander, 1910). This has since been discredited and recent flux studies, have supported stratigraphic evidence that hollows can represent a net loss to the system whereas hummocks and lawns can accumulate carbon (Bubier et al., 1995; Waddington & Roulet, 2000). The long-term water table position is also related to the carbon balance of bogs in a complex manner. However, vegetation cover can be a useful indicator of carbon flux and bryophyte communities are good predictors of CH_4 flux because the distribution of bryophytes is related to the long-term water table position (Bubier et al., 1995). The most important peat forming vegetation includes *Sphagnum* spp. and members of the Cyperaceae and Ericaceae. Variability exists in the contribution to peat formation between and within these groups.

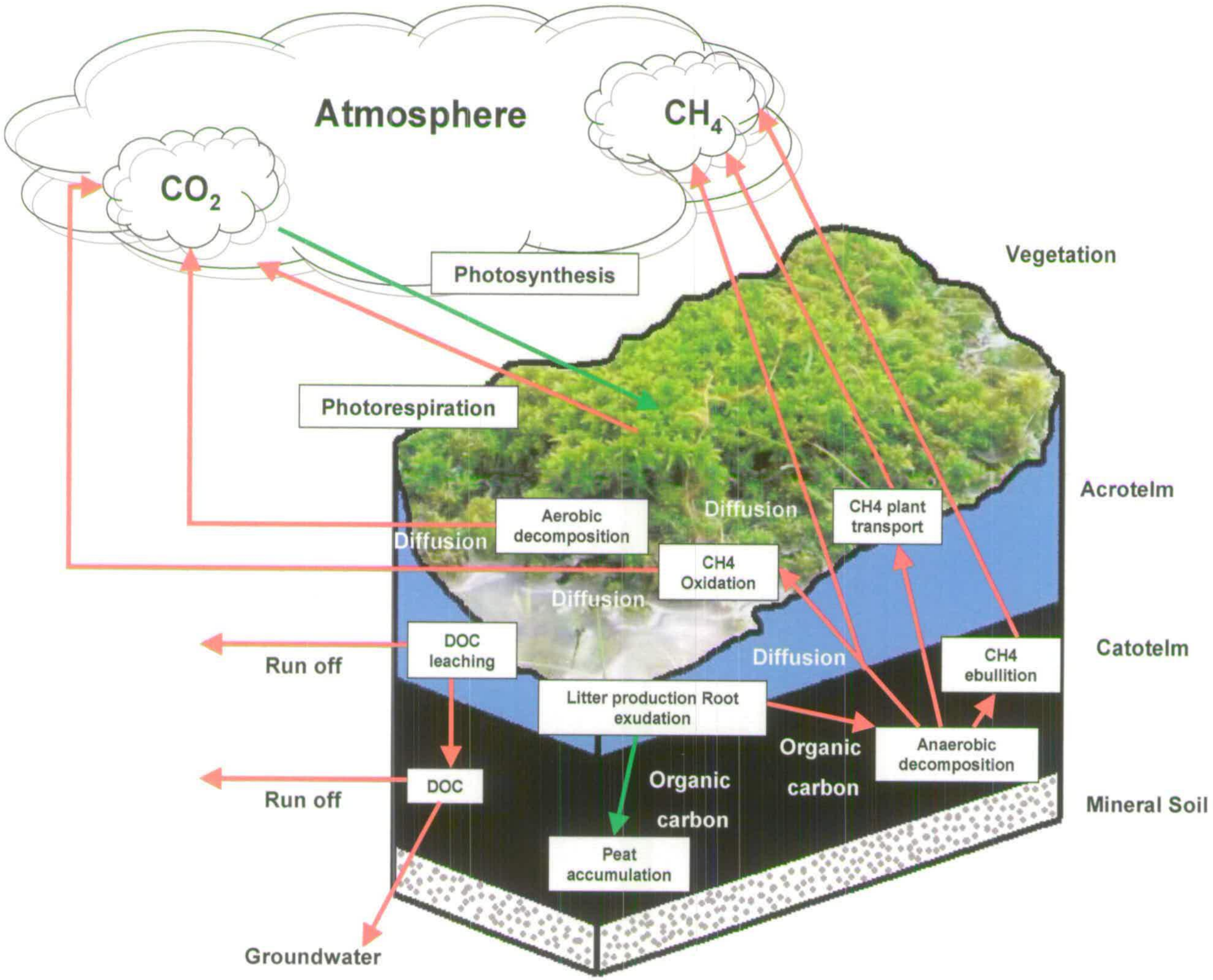

Figure 1.3: Schematic representation of the peatland carbon cycle, red arrows = losses of carbon, green arrows = gains of carbon.

1.3.1 Carbon Dioxide

The exchange of carbon dioxide in peatland ecosystems mirrors that of most other terrestrial ecosystems; inputs are gained by photosynthetic activity of plants and micro-organisms. There may also be deposition of carbon in precipitation but this is unlikely to be a significant amount. Losses are accounted for by respiration, aerobic decomposition, and the oxidation of methane by anaerobic decomposition in the catotelm. The balance between these inputs and outputs determines whether the system is a sink for carbon dioxide or a source (whether the system is an overall sink is determined by taking into account all other forms of carbon). By convention a flow of carbon into the system has a negative value and sources are given a positive value and this convention is adopted throughout this thesis. Thus the balance for carbon dioxide can be represented by the following simple related equations:

$$\mathrm{NEP} = P - R_p - R_h$$

$$\mathrm{NPP} = P - R_p$$

$$\mathrm{GPP} = P$$

Where NEP is Net Ecosystem Productivity (also called net ecosystem exchange, NEE), P is CO_2 uptake by photosynthetic activity, R_p represents respiration by plants R_h respiration by heterotrophic organisms, NPP is Net Primary Productivity and GPP is Gross Primary Productivity (Grace, 2004).

Upland productivity (NPP) in the UK has been measured historically by clipping experiments where vegetation was marked and after a defined period of time, removed, dried and weighed (Welch & Rawes, 1965; Clymo, 1970; Clymo & Reddaway, 1971; Forrest, 1971; Clymo & Reddaway, 1972; Forrest & Smith, 1975; Rawes & Hobbs, 1979; Rawes, 1981, 1983).

There is now a growing amount of literature examining various aspects of these ecosystem productivity relationships in peatlands on a variety of scales from leaf to entire ecosystems, using a wider variety of techniques than just harvesting such as static and dynamic chambers or micro-meteorological methods like eddy-covariance, especially in North America and Scandinavia. Static (non-steady state) and dynamic (steady state) chambers differ in that static chambers do not have a gas flow system and enclose a headspace above vegetation or soil, fluxes are then calculated from changes in the original headspace gas concentration, dynamic chamber fluxes are calculated from the change in gas concentration of the gas flowing through the chamber from input to output. In the UK gaseous exchange research gained momentum during the TIGER programme (Oliver et al., 1998) but the majority of work in the UK on blanket bog has centred on quantifying fluxes of methane (See Chapter 2). One puzzling aspect of carbon flux research is the large range of units reported in the literature and these do not always explicitly state which chemical compound or element they relate to, for discussion of this see Appendix.

1.3.2 Methane

Peatlands emit methane, as do all wetlands, as a by-product of microbial anaerobic decomposition. Recent suggestions of aerobic methane production by terrestrial plants remain controversial (Keppler et al., 2006) but if confirmed these emissions are likely to be dwarfed by several orders of magnitude by peatland emissions. There has been much research to date on the emissions of methane from northern wetlands including blanket bog. These indicate there are large temporal and spatial variations in CH_4 emission rates that need to be taken into consideration. The following examination of the controls on methane emissions is largely from two reviews (Bubier & Moore, 1994; Joabsson et al., 1999). Depth of water table, soil temperature and vegetation type have been identified as controls of CH_4 production and net CH_4 emissions. Species differences in physiology and morphology make the effects of vascular plant functioning on net CH_4 emissions difficult to predict. Correlations between environmental variables and CH_4 emission have been established and variables are very strongly inter-related and often counteract each other. Estimates for emissions vary (Whalen & Reeburgh, 1992) suggest tussock tundra globally emits 42 +/- 26 Tg yr^{-1} but other studies (see Bubier and Moore, 1994, Joabsson *et al.,* 1999, and references therein) estimate emissions in the region of 18-35 Tg yr^{-1}. Sites largely similar in vegetation and topography display large differences in emissions when between-sample differences in vegetation classification and climate are taken into consideration. Water table is a strong predictor of CH_4 flux therefore vegetation patterns may be useful in predicting CH_4 flux but to date there has been no agreement of spatial scales or the system of vegetation classification in the different studies conducted. The solubility of CH_4 is low (23-40 mg l^{-1} at 0-20 °C) therefore, CH_4 can escape through diffusion bubble ebullition or transport through vascular plants through aerenchymatous tissue. Studies in rice paddy fields indicate that 90% of CH_4 flux arises from the tillers of rice. Root transport of oxygen to the soil can impact on mechanisms of methane production and oxidation. This transport can reduce methanogenic bacterial activity but CH_4 oxidation may be stimulated, as methanotrophic bacteria are O_2 limited. However the net effect of roots may increase CH_4 emissions as models suggest CH_4 transport in soil is reduced without roots. The atmosphere constitutes a sink for CH_4 thus a diffusion gradient exists. Increased CH_4 oxidation would decrease this gradient but increases in organic substrate released by plants would increase methanogenesis and hence the gradient. Stomatal closure is partly effective in reducing emissions but emissions are still evident even when stomata are closed. However, this indicates that species composition is important to the control of CH_4 emissions. Methanogenic bacteria use simple substrates and initially rely on other bacteria to break down complex organic molecules into simpler molecules. Positive correlations between net primary production (NPP) and CH_4 emission have been used to suggest an association between new plant production and methanogenesis (Whiting & Chanton, 1993). However, a causal link seems unlikely since the two processes are separated spatially and temporally (in terms of the substrate from plant production reaching methanogens which would at least lead to a time lag) and it would seem more likely that both effects are related to temperature. Some work also suggests links between light intensity and emissions of methane (Lloyd et al., 1998) again this is correlative, light effects may be indirect and emissions may be more directly related to changes in temperature and stomatal conductance.

1.3.3 Peatland Carbon Fluxes to River Systems

This section is intended as an introduction to peatland carbon exports to river systems and does not represent an exhaustive review. Carbon exports from peatland ecosystems to rivers are mainly composed of dissolved organic carbon (DOC), particulate organic carbon (POC), dissolved inorganic carbon (DIC), and dissolved CO_2 and CH_4 (Dawson et al., 2002). The amount of carbon that is transported annually is thought to be one or two orders of magnitude lower than the exchanges commonly found between vegetation and the atmosphere or between the atmosphere and oceans.

DIC is composed of HCO_3^- ions and free dissolved CO_2 associated with gaseous carbon dioxide via the carbonate equilibrium (Stum & Morgan, 1981, cited in Dawson et al., 2002). Free CO_2 outgases further downstream until reaching equilibrium with the atmosphere and concentrations show diurnal and seasonal variation (Dawson et al., 2001). Losses of free CO_2 can also be attributed to photosynthetic activity of aquatic plants and phytoplankton but quantifying this seems elusive at present (Dawson et al., 2001).

The distinction between POC and DOC is based on size. POC ranges between 0.45 and 1.0 µm and DOC includes suspended particles below 0.45 µm (Dawson et al., 2002). Isotopic evidence points to the terrestrial origins of stream DOC and suggests that most may be of recent origin (post-AD 1955) (Palmer et al., 2001); in other words the majority of the DOC in streams is not produced there but transported from other systems. Dissolved organic matter (DOM) includes other compounds as well as those containing carbon; DOC is about 50% of DOM (Tipping et al., 1999).

Our understanding of how organic matter is mineralized and partitioned into carbon dioxide, methane, and dissolved organic carbon is still lacking (Blodau, 2002). In Canada it has been estimated that between 2.4–5.6% of the peat carbon is mineralized annually (59 - 140 µg C g^{-1}peat d^{-1}) from floating peat islands in reservoirs (St Louis et al., 2003) the authors suggest that fluxes of CO_2 and CH_4 from peat could last 18–42 years from point of entry into the reservoir. However, the partitioning to different carbon products was not addressed. Intuitively the larger the organic pool in the catchment area the higher the DOC output, but this is also affected by stream physics such as discharge rate (Dawson et al., 2002). DOC can affect downstream aquatic net primary production (Carpenter and Pace 1997, in Pastor, *et al.*, 2003), microbial production (Hobbie 1992, Wetzel 1992 cited in Pastor, *et al.*, 2003) and other biogeochemical cycles (Driscoll et al. 1980, Hemond

1980, Jackson and Hecky 1980, McKnight et al. 1985, Thurman 1985, Guildford et al. 1987, in Pastor, *et al.*, 2003) and can also attenuate visible solar and UV-B radiation (Schindler et al. 1990, 1996, Scully and Lean 1994, Morris et al. 1995, Williamson et al. 1999, in Pastor, *et al.*, 2003). Losses of DOC within the stream system can be attributed to biotic as well as abiotic sources such as biofilm respiration, adsorption to algae and mineral surfaces, particularly Fe and Al oxides, and hydroxides (Pastor et al., 2003). The composition of DOC is also important when considering fluxes to the atmosphere. Approximately 20% is low molecular weight compounds such as carbohydrates, amino acids, peptides, nucleic acids and carboxylic acids that represent a ready resource to the biota (Thomas 1997, in Dawson 2001). The remaining 80% tends to be phenolics and fulvic, humic and hydrophilic acids that represent more refractory compounds (Thurman 1985, in Dawson 2001). This suggests that the majority of the DOC resource is difficult to break down and may take a long time to reach the atmosphere in the form of gaseous emissions.

Although there can be significant outputs from peatland systems as implied above, the overall effects of these outputs in terms of the impact upon greenhouse gas emissions are still unclear. A significant proportion of POC may be stored in the sediments and DOC is transported through the river system (Worrall et al., 2003b), presumably either being consumed in the stream or eventually reaching the ocean.

There has been an observed trend of increasing DOC concentrations in river catchments in the UK over the last two decades (Monteith & Evans, 2000; Worrall et al., 2003a; Worrall et al., 2004a; Worrall & Burt, 2005). The reason for this remains elusive but is likely to be a combination of complex factors, for example climate change and its influence on microbial processes (Freeman et al., 2001a; Worrall et al., 2004a; Worrall et al., 2004b). There are at least three mechanisms whereby climatic change could affect the DOC budget of peatlands (Pastor et al., 2003):

- increased temperatures could increase the production (through increased decay rates) and/or microbial consumption of DOC, thereby changing DOC concentrations in drainage water,

- changes in the position of the water-table level could change DOC concentrations as different portions of the peat profile become susceptible to aerobic and/or anaerobic decomposition regimes, and
- changes in the water budget and discharge could control DOC export independently of any changes in DOC concentrations.

Attempts to model the increase in DOC in the UK in relation to temperature and water table have not been successful (Worrall et al., 2004a). It appears that it is difficult to achieve a model that is an adequate representation of the processes that it attempts to explore. Daulat and Clymo (1998) consider that reporting the relationship between methane and temperature by activation energies in an Arrhenius plot is misleading, since there are probably complex causes. It is worth noting that an Arrhenius approach was used in the model for production of DOC by Worrall et al., (2004a). Perhaps DOC production needs to be considered as a more complex process. Indeed, in a subsequent model the lack of complexity is acknowledged (Worrall & Burt, 2005). As no one process accounts for such a complex biological phenomenon as the production of DOC it should be expected that simplified models ultimately fail, but in their failure they can reveal issues that require clarification. Worrall, *et al.,* (2004a) consider the 'enzymatic latch' (Freeman et al., 2001b) the most likely explanation of their results. This proposes that the absence of oxygen in peatland environments is responsible for the inhibition of the enzyme phenol oxidase (Freeman et al., 2001b). Phenol oxidase increases decomposition as the recalcitrant phenols are broken down which would happen when water tables are lowered (Worrall et al., 2004a). Freeman et al., (2001) reported a doubling of CO_2 flux with a doubling of phenol oxidase. As noted above DOC comprises low molecular weight compounds such as carbohydrates, amino acids, peptides, nucleic acids and carboxylic acids, refractory phenolics, and fulvic, humic and hydrophilic acids (Thomas 1997 in Dawson 2001). Therefore an increase in phenol oxidase activity should lead to further breakdown of complex organic compounds that make up DOC and an increase in CO_2 flux; not to a simple increase in the production of DOC as proposed by Worrall, et al., (2004a). However, perhaps the increase in phenol oxidase activity leads to a preferentially increased rate of breakdown of larger fragments of POC thus producing more DOC. This poses an interesting question; do substrates of similar composition but differing particle sizes decompose at different rates? St. Louis et al., (2003) found that rates of mineralization of peat pieces were not different from rates of mineralization of larger peat blocks in reservoirs but these were much larger fragments than the particle sizes of POC or DOC. If this relationship follows for POC and DOC decomposition, then both should decompose at the same rate thereby still leading to a reduction in total DOC due to faster decomposition rates under higher phenol oxidase activity. In a study on Great Dun Fell, England it was found, contrary to the theory of Worrall, et al., (2004a) that DOM production was in fact lower during the lower water tables of drought conditions (Scott et al., 1998) . Also, molecular changes in the composition of DOC were noted indicating that changes to the decomposition process were evident (Scott et al., 1998; Scott et al., 2001). Conversely clear responses to temperature were found in a lysimeter transplant experiment in relation to a peaty gley and DOC production in northern England (Tipping et al., 1999). This may be in part due to enchytraeid worms, as a positive response between temperature, DOC concentration and enchytraeid abundance has been found in the northern Pennines (Cole et al., 2002). DOC production is undoubtedly a very dynamic process with factors such as temperature, oxygen availability and moisture influencing chemical degradation, solute dissolution and microbial activity (Scott et al., 2001).

In considering all the points above and in relation to the recent increase in DOC production in the UK, we need to ask whether future DOC production will continue to increase. If this does indeed happen will stream processes increase the conversion of DOC to gaseous emissions to the atmosphere, and if so will this increase continue indefinitely? It may be that riverine ecosystems have a kind of carrying capacity for DOC and inputs above this capacity would increase transfer of DOC from terrestrial systems to rivers and thereby to the ocean, but not necessarily increase losses to the atmosphere. The question is does this carrying capacity exist and if so what controls influence it, for example, biotic population sizes, availability of mineral substrates, or temperature? This could have important implications for modelling the contribution of this type of carbon export from peatland systems to atmospheric carbon budgets.

This limited review of carbon export from peatlands to river systems has found no work investigating this hypothesis.

Estimated outputs in temperate and boreal river systems have been reported to vary between 10 and 100 kg C ha^{-1} yr^{-1} (Hope et al., 1997) on the higher end of this range the river Halladale in a blanket bog catchment in Sutherland has been recorded with an output of 103.4 kg C ha^{-1} yr^{-1} (Hope et al., 1997) (see Appendix for tables of reported fluxes) . It is encouraging that most authors record information on the management of the catchment areas they are researching, (DOC outputs are tabluated in the Appendix). There remain though, some fundamental questions requiring research particularly involving the mechanisms of DOC production, the influence of climate and the transfer of DOC to the atmosphere.

1.4 UK Peatlands and the Greenhouse Gas Inventory (GGI)

The UK ratified The United Nations Framework Convention on Climate Change (UNFCCC) in December 1993 which came into force in March 1994 (Baggott et al., 2004). Implicit in the convention is the development, publishing and regular updating of estimates of national emission inventories for greenhouse gases (GHGs). The UK publishes figures annually; the greenhouse gases reported are:

Direct Greenhouse Gases

- Carbon dioxide (CO_2)
- Methane (CH_4)
- Nitrous oxide (N_2O)
- Hydrofluorocarbons (HFCs)
- Perfluorocarbons (PFCs)
- Sulphur hexafluoride (SF_6)

Indirect Greenhouse Gases

- Nitrogen oxides (NO_x, as NO_2)
- Carbon monoxide (CO)
- Non-Methane Volatile Organic Compounds (NMVOC)
- Sulphur dioxide (SO_2)

In the context of blanket bog the most significant of these gases are CO_2, and CH_4, since these gases are emitted and sequestered as part of biological processes. At present peatlands in the UK contribute to the inventory as part of the land use change and forestry category, appearing as the upland drainage and peat extraction for fuel and horticulture sections in the sub-category 'other'. The total emissions reported for land use change and forestry were approximately 2.5% of the UK total in 2002 and are declining gradually but this was attenuated by the estimated removal of nearly 11682 Gg of CO_2 (~2% of total emissions) by uptake in photosynthesis of forests (changes in woody biomass stock) and agricultural crops (removals in sub-category 'other') (Baggott et al., 2004); see Table 1.3.

Table 1.3: Summary of sources and sinks of greenhouse gases important to UK peatlands for the year 2002. Units are Gg CO_2 equivalents, (Baggott et al., 2004).

Greenhouse gas source sink	**CO_2 emission**	**CO_2 removal**	**CH_4**	**N_2O**
Total UK National	**550965**	**-11682**	**2098.4**	**132**
Land use change and forestry total	13585	-11682	1.1	0.1
Changes in woody biomass stock	-	-10582	-	-
Forest and Grassland Conversion	259	1.1	0.1	-
CO2 emissions and removals from soils	9937	Included elsewhere	-	-
Other Total	**3389**	-1100	-	-

Scotland is important to this in the greenhouse inventory for two reasons. Firstly, by far the highest density (t ha^{-1}) of carbon in the UK's soils is found in Scotland, attributable to the extent of natural soils the majority of which are peatland (Table 1.4). Secondly, because the inventory takes account of drainage of upland peat soils due to afforestation, the majority of which occurs in Scotland (Table 1.5), this is counted as a source of CO_2, therefore the majority of this emission originates in Scotland. Upland drainage and peat extraction account for over 60% of the subcategory 'other' (Table 1.6).

Table 1.4: Average soil carbon density (t C ha^{-1}) for different land cover in the UK (Baggott et al., 2004). The high carbon content of the natural category is due to the inclusion of blanket bog and other peaty soils.

Region cover	England	Scotland	Wales	N. Ireland
Natural	487	1048	305	551
Woodland	217	580	228	563
Farm (Arable)	153	156	93	151
Farm Pasture	170	192	200	178
Other	33	141	43	102

Table 1.5: Activity and Emission Factor Data for Upland Drainage

	Afforested Peat (kha)	Emission rate (t C $ha^{-1}a^{-1}$)	Annual Loss (kt C)
England	20	2	40
Wales	10	2	20
Scotland	160	2	320
Northern Ireland	10	2	20
UK	200	2	400

Table 1.6: Breakdown of the contribution of upland drainage and peat extraction to subcategory 'other' (Table 4) adapted from Baggott, *et al.*, (2004) units are Gg CO_2 equivalents for the year 2002.

Greenhouse gas source sink	**CO2 emission (Gg CO_2)**	**% of emissions from other sub-category**
Total Other	**3389**	100
Upland Drainage	1466.67	43.3
Peat extraction	682.92	20.2

1.4.1 GGI and Unaccounted Emissions from Peatland

At present most emissions from land-use change and forestry arise from the emissions of CO_2 from soil, which includes the cultivation of mineral soils, liming of agricultural soils and drainage, although there is an acknowledge 60% uncertainty in the values for emissions from soils (Baggott et al., 2004). As already stated the majority of upland drainage occurs in Scotland. However, the inventory only includes drainage on upland soils due to afforestation, there is no account for drainage due to moor-gripping, which, although there is no quantitative estimate of the geographical extent, is widespread. This is probably due to the cessation of moor-gripping in recent times and land use change is only accounted for after 1990 (Baggott et al., 2004). However, if restoration of peatlands is taken up on a large sale then the consequences on carbon budget should be taken account of.

Methane emissions from land-use change and forestry are accounted for entirely by the Forest and Grassland conversion category and arise from emissions from forests (Baggott et al., 2004). However, it has been suggested that under the terms of the Kyoto Protocol, peatlands could be used to meet reduction targets of carbon emissions under grazing land (Worrall et al., 2003b). If this is a realistic scenario it will be vital to take account of methane as well as carbon dioxide from peatlands. Further, restoration projects on blanket bog in Scotland affect both afforested and drained bogs and undoubtedly affect the carbon balance in the process. However, given the limited geographical extent of restoration projects at present this is unlikely to affect the greenhouse inventory greatly but if extended to larger areas information on the effects of these projects will be required to feed directly into the greenhouse inventory.

1.5 Review of the effects of management on blanket bog and hypothetical effects on carbon fluxes

This section summarises the effects of management on the biological components of blanket bog and then speculates what the effect of these may be on the carbon balance of the peatland. There are few direct measurements of the effect of management on carbon dynamics but see Garnett, (1998) and Garnett *et al.* (2000).

1.5.1 Grazing

Shaw et al., (1996) reviewed the effects of grazing on blanket bog and wet heath and offer a more detailed examination of grazing than can be found here but much of what follows is adapted from that review. It seems likely that all areas of blanket bog in the UK are, or have been, subjected to grazing by both domestic and wild animals, and for the past 150-200 years rotational burning and grazing have been regularly practiced (Shaw et al., 1996). Grazing, like burning, may also be a contributory factor in the initiation of blanket peats in the UK (Shaw et al., 1996). Although it was not the primary objective of Shaw et al., (1996) to examine how management practices affect the carbon balance of blanket bog, their following points are worthy of note.

- The effects of grazing vary according to stocking rates, wetness and condition of the site, type of grazing animal, time of year and length of time spent on the site.

- Changes in vegetation composition and damage can be the result of trampling, which if severe, may result in bare ground. Effects can be localized, for example, around feeding points, fences, walls, etc. These areas are also affected by enrichment from dung and urine.

- The effects of grazing on vegetation vary depending on the availability to herbivores of other habitats and food resources. There are interactions between management history and grazing that are difficult to separate, for example, grazing is often associated with burning.

The immediate effect of grazing is a removal of vegetation and continual grazing can lead to a change in composition and structure such as the loss of heath to more *Molinia* and *Eriophorum* dominated vegetation (Shaw et al., 1996). Stocking rates are regionally variable and are partly dependent on the availability of other habitats for feeding. They can also be difficult to assess for example, Shaw et al., (1996) cite a ewe unit, which may include horses, and ewe counts which do not include lambs. Seasonality of use is also not reflected in stocking rates as a heavy winter and light summer use are evened out over the year (Shaw et al., 1996). Optimal stocking rates in terms of animal condition and with respect to vegetation would appear to be low but there is no definitive figure, this is dependent on location, site condition, climate, vegetation, etc. but is likely to be below 0.37 ewe ha^{-1} (Rawes & Hobbs, 1979; Shaw et al., 1996).

The type of grazing animal can have an effect because of the different oral morphology and behaviour exhibited during the period on site. Cattle wrap their tongues round the vegetation and rip plants up; together with poaching this tends to produce a tussocky sward. Cattle are also less selective in diet preference than sheep (Shaw et al., 1996). Sheep bite and shear vegetation producing a much more even sward and are not as heavy. Breed and stock type can also show different effects as ewe and lambs are more selective in diet choice than wethers (Shaw et al., 1996). Goats have more of a preference for browsing woody vegetation. Horses and ponies tend to be less important in numbers on bogs but may be locally important for example on Exmoor and Shetland. Ponies tend to use the same site repeatedly for defecation leading to local areas of enrichment. Red deer are similar to sheep in their diet preference but proportionally eat less grass. Competition for the same areas may exacerbate damage but it is often difficult to separate the effects due to the different species (Shaw et al., 1996). Deer tend to prefer older rather than pioneer *Calluna*, grouse on the other hand require younger *Calluna* stems. Hares also favour pioneer *Calluna* and numbers can correlate with burning; like deer they can prevent regeneration of trees and in some cases *Calluna* (Shaw et al., 1996). Voles tend to prefer sites with *Juncus* and *Molinia* (Shaw et al., 1996) though not strictly 'classic' blanket bog vegetation these species can be prevalent on modified bog on deep peat.

Seasonality of grazing also affects the disturbance to the site and vegetation, for example, *Calluna* tends to be eaten more in winter when grasses are less available this can lead to susceptibility to winter browning (wind and frost damage) if grazing is very heavy (Shaw et al., 1996).

Before moving on to other management practices it is useful to examine the interactions of management practices. Thompson et al., (1995) present a simplified vegetation succession diagram, reproduced in Figure 1.4, useful in general terms for assessing interactions between burning, grazing and water table alteration. Although simplified this model is useful for examining relationships, however not all of it is based on evidence and some of the transitions are assumed (Shaw et al., 1996).

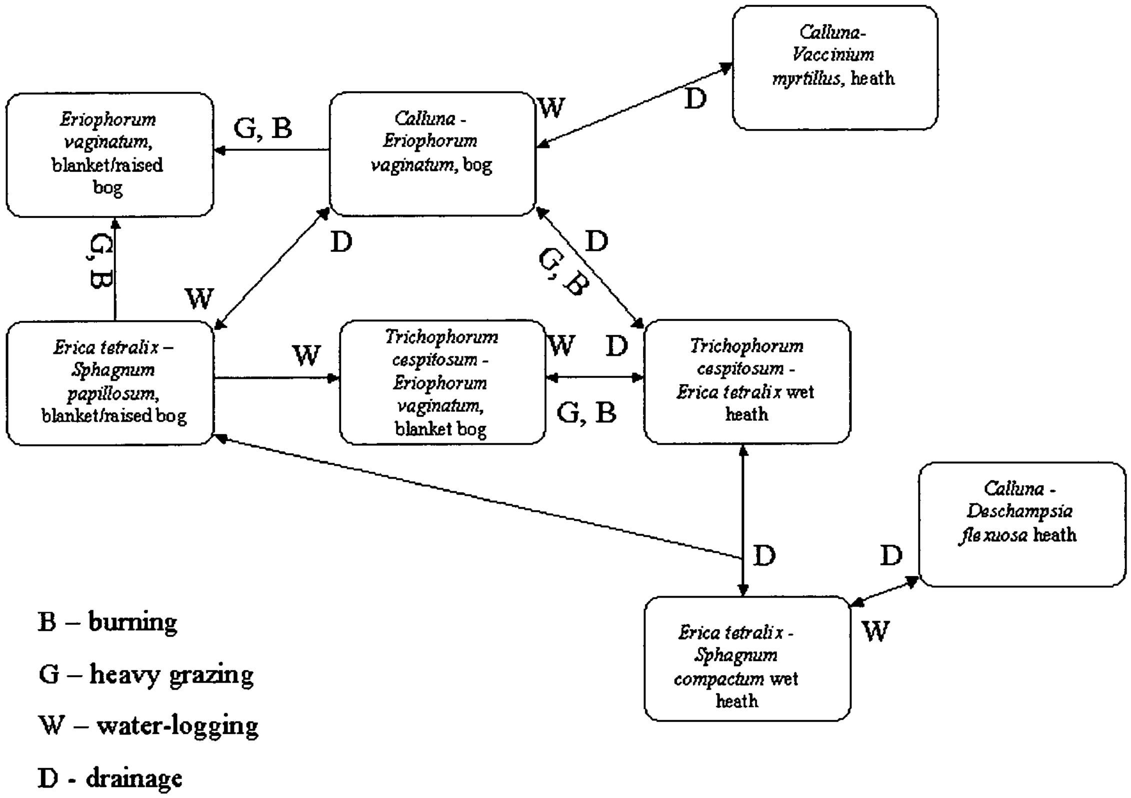

Figure 1.4: Simplified successional changes between bog and heath communities as affected by burning grazing and water table alteration (re-drawn from Thompson *et al.,* 1995, cited in Shaw *et al.,* 1996).

1.5.2 Hypothesized Effect of Grazing on the Carbon Balance of Blanket Bog

Grazing affects the carbon balance through effects on the vegetation (Figure 1.4), physical and chemical environment. These effects will vary according to the time spent in the habitat, season, animal species, breed, sex, age, and associated behaviour related to feeding, defecation, urination, travel and shelter.

1. Vegetation

The physical acts of feeding and trampling can lead to the altering of vegetation composition structure and may lead to complete destruction of vegetation thereby leading to areas of bare peat. Altered vegetation composition will affect both photosynthesis and photorespiration altering the inputs and outputs of carbon dioxide to and from the atmosphere. A different vegetation composition would lead to an alteration of microbial decomposition in an unknown manner because of the different physical structure and chemical composition of different species. To date, the quantification of the effects of grazing on carbon fluxes has not been explored fully.

2. Physical

Physical changes to the peat may come about through compaction by trampling and in extreme cases lead to erosion, see below. Through the actions of trampling and feeding the structure of the vegetation is also altered, thus altering carbon dynamics.

3. Chemical

The nutrient balance of the bog can be altered by defecation, urination and the removal of plant matter. Further the removal of animals for slaughter or to other areas outside the blanket bog essentially translates to a removal of nutrients from the system. As carbon based life-forms this inevitably involves the transport of carbon out of the blanket bog system. Rawes and Heal (1978) (in Shaw *et al.,* 1996) consider that there is little or no net income or loss from the bog in terms of N, P, K and Ca, but this work was conducted in the Pennines, which may be atypical in comparison to other areas of blanket bog in the UK in terms of utilisation for livestock. This carbon loss from the system will be transferred to the atmosphere in the short term as it is processed into food.

1.5.3 Burning

Shaw et al., (1996) and Tucker (2003) reviewed the effects of burning on blanket bog and wet heath and more detailed examination can be found in these references. Although it was not the primary objective of these reviews to examine how management practices affect the carbon balance of blanket bog, the majority of what follows is summarized from these reviews. The following summary points from Shaw *et al.,* (1996) are of note.

- Most of the work to date investigating burning as a management tool has been conducted on grouse moors or lowland heaths, and so relates to a drier type of habitat than blanket bog.

- Burning has physical, chemical and biological effects. The effects of fire are dependant on the vegetation, intensity and frequency of the fire, timing of the burn and the wetness of the habitat. Summer fires are likely to be most damaging for wildlife interest.

- There will be indirect effects through changes in the physical habitat characteristics, plant species composition and vegetation structure and consequently microclimate.

Tucker (2003) summarised the impact of fire on selected upland species and the impacts on those species more prevalent in blanket bog are reproduced in Table 1.7 and Table 1.8. For a simplified model of how fire affects vegetation see Figure 1.3 above.

Burning has been used for centuries and some authors believe that anthropogenic fire may have been responsible for he initiation of blanket bog in some areas (Moore et al., 1984), certainly evidence stretches as far back as Mesolithic period (Shaw et al., 1996). The intensity of fires varies according to the temperature reached and the speed. In extreme cases intense fires can ignite the peat removing the vegetation, produce a hard bitumen surface that can lead to increased runoff increased exposure increased heat and evaporation and an increased amplitude of temperature fluctuation decreased soil organic matter and nutrients, and seed bank destruction therefore making it difficult for plants to establish and may lead to erosion. This type of fire is more likely when ignition is accidental or malicious (Maltby et al., 1990; Legg et al., 1992; Tucker, 2003). The goal of managed fire is to remove and regenerate vegetation to improve food quality and vegetation structure, for example, *Calluna* for red grouse or grass and sedges for the 'early bite' (Shaw et al., 1996; Hamilton et al., 1997; Hamilton, 2000; Tucker, 2003). This latter strategy is used particularly on blanket bog in the north west of Scotland (Hamilton et al., 1997; Hamilton, 2000). Guidance on the use of fire is contained in the Muirburn Code (Anon, 2001), generally the burning of blanket bog is not recommended because of the detrimental effect it can have on the characteristic species and the risk of peat ignition, except where *Calluna* constitutes more than 75% of the vegetation (Anon, 2001) but these should be on long rotations (Shaw et al., 1996, Tucker, 2003, and references therein). However, *Sphagnum* species are not as sensitive as perhaps is assumed and do not always do badly under fire management (Hamilton, 2000; Tucker, 2003). There can also be interactions between fire and drainage because the water level can influence the effects of the fire as moist peat is insulated and severe burning can lead to increased peak flows in drainage ditches (Shaw et al., 1996).

In concluding, Shaw *et al.,* (1996) state that when burning (and grazing) are carried out indiscriminately these management practices are likely to be damaging to the wildlife interests of blanket bog and may even lead to loss of habitat. However, if conducted sensitively, both burning and grazing can have beneficial effects to some species of these habitats (though not all).

Table 1.7: Summary of impacts of burning management on selected blanket bog species, species groups and blanket bog habitat based on Tucker (2003) and Hobbs *et al.*, (1984).

Species	**Perennating organ & fire survival mechanism**	**Impacts**
Calluna vulgaris	Stem bases, protected by litter and persistent seed bank	Regenerates relatively rapidly after typical management fires, if burnt before the late mature phase. Re-establishes by seed from abundant long-lived seedbank if old stands are burnt or if hot fires damage basal stems. But seedling establishment is slow and may allow invasion by rhizomatous species. May not re-establish if burning is too frequent. Generally increases in abundance with long burning rotations (e.g. > 15 years) on bogs.
Empetrum nigrum	Buried branches	May be susceptible to fires but if prostrate stems are not destroyed then may gain temporary dominance in heathlands until overtopped by *Calluna.*
Erica tetralix	Stem bases, protected by litter and persistent seed bank	Similar to *Calluna*, but favoured by shorter burning rotations of 6-10 years. May also be able to regenerate better in wetter habitats because its semi-prostrate lower branches are protected by *Sphagnum* and litter layers.

Table 1.7 continued

Species	**Perennating organ & fire survival mechanism**	**Impacts**
Eriophorum angustifolium	Rhizomes	Often benefits from periodic fires, as can rapidly recolonise burnt areas from rhizomes, but is later out competed. May not survive post-fire conditions if significant changes in moisture and pH.
Eriophorum vaginatum	Tiller apices within leaf sheaves	Rapidly regenerates after fire and probably resistant to hot fires due to tussocky growth form. Temporarily dominates after fires in blanket bogs and can remain dominant if burning rotations are less than 10 years.
Molinia caerulea	Tiller apices within leaf sheaves	Can regenerate rapidly after fire and often dominates (sometimes with *E. vaginatum*) under frequent burning regimes.
Sphagnum mosses	-	Often thought to be fire sensitive, but little evidence for this. Wet conditions may protect species from fires and some can regenerate from deep buried fragments. Most impacts probably from peat damage and trampling, or due to exposure to drying or algal growth after removal of vegetation cover.

Table 1.8 Extent of the practice of burning and advantages and disadvantages of this type of management on the blanket bog habitat (Tucker, 2003)

Habitat	**Extent of burning**	**Advantages**	**Disadvantages**
Blanket Bog	Majority under some sort of burning regime	*Eriophorum* favoured may benefit black grouse and large heath butterfly if abundance low. Some carefully selected controlled burning may be necessary to reduce fuel loads and risk of wild fire	Potential loss of fire sensitive species; can become dominated by *Eriophorum* on short rotations, or *Calluna* on long rotations. Nutrient loss may be significant Reduced peat formation and significant risk of erosion and combustion of peat. Peat combustion and drying causes significant losses of carbon. Increased *Eriophorum* may cause increased methane flux.

1.5.4 Hypothesized Effect of Burning on the Carbon Balance of Blanket Bog

Again as with grazing there are effects on the vegetation, physical and chemical environments, which will depend on the frequency intensity of the fire. An additional loss of carbon and other chemicals through fire will be to the atmosphere in smoke and ash. The consequences of fire on carbon balance will also be scale dependent. While the immediate consequences of fire are the loss of carbon to the atmosphere and death of important peat-forming species such as *Sphagnum*, in the intermediate term, the removal of shrub cover and litter may permit rapid recovery and expansion of *Sphagnum* and peat formation. In the long term, fire may promote increased *Calluna* dominance and changes to the hydrology of the bog that result in desiccation and oxidation of peat (Hamilton, 2000). There is also evidence that the perturbation of fire stimulates microbial activity within peat and probably increases the rate of decomposition (Maltby et al., 1990). Rates of peat accumulation have also been noted to be lower in areas that are burnt (Kuhry, 1994; Garnett, 1998; Garnett et al., 2000) suggesting that in terms of carbon sequestration burning may not be beneficial. Severe fire can lead to the direct combustion of peat and may lead to erosion thus exacerbating the carbon loss (Tucker, 2003). However the long-term impacts of burning are more complex than it would first appear as *Calluna* accumulates more carbon in the building and mature phases (Tucker, 2003). The removal of a dense shrub canopy has also been observed to benefit the recovery of *Sphagnum* species in some bogs (personal observation) this may be brought about by fire or other mechanical means with unknown implications for the carbon balance.

1. Vegetation

The removal of vegetation through burning alters vegetation structure and competitive interactions between species thus leading to altered species composition. An increase in *Eriophorum* may cause increased methane flux to the atmosphere. Although burning is a different process, both burning and grazing affect the vegetation composition and structure and will therefore alter the carbon related processes of photosynthesis and respiration. To date, the quantification of the effects of burning on carbon fluxes on blanket bog has not yet been explored fully.

2. Physical

Physical changes to the peat depend on the frequency and intensity of the fire these are most likely to be extreme when associated with accidental fires with a high fuel load and that may lead to erosion and thus a loss of carbon, see below.

3. Hydrological

Burning reduces the water storage capacity of the peat and, again, in extreme conditions may lead to areas of bare peat; these may increase evaporation and runoff which are likely to increase fluxes of DOC, etc. from the peatland system. The alteration of storage capacity may also lead to an altered water table thereby altering the balance between aerobic and anaerobic decomposition with consequences for the carbon balance.

4. Chemical

Burning causes a short-term availability of nutrients and alteration to pH but there are undoubted losses from the system including carbon. Even though there is replacement from atmospheric inputs, there may be long-term shortfalls in the replacement of N, P and K (Tucker, 2003). The implications for this on the carbon dynamics are unknown at present most studies are limited in that they are concerned with short-term rather than long-term impacts (Tucker, 2003), but there will be impacts upon biological processes from the changing of nutrient availability. This will be further complicated by increased deposition of chemicals in upland areas from industrial pollution.

1.5.5 Drainage

The practice of moor gripping on blanket peats has been continued for a number of centuries. Original drains were cut by hand but in more modern times by machine. Drains vary in size and depth. Drains can range from single drains for boundary demarcation to extensive herring bone patterns of moor grips 40-50 cm deep (see Figure 1.5). The desired effects of drainage are a lowering of the water table thus leading to an altered vegetation and more desirable area for sporting and agricultural activities (Coupar et al., 1997).

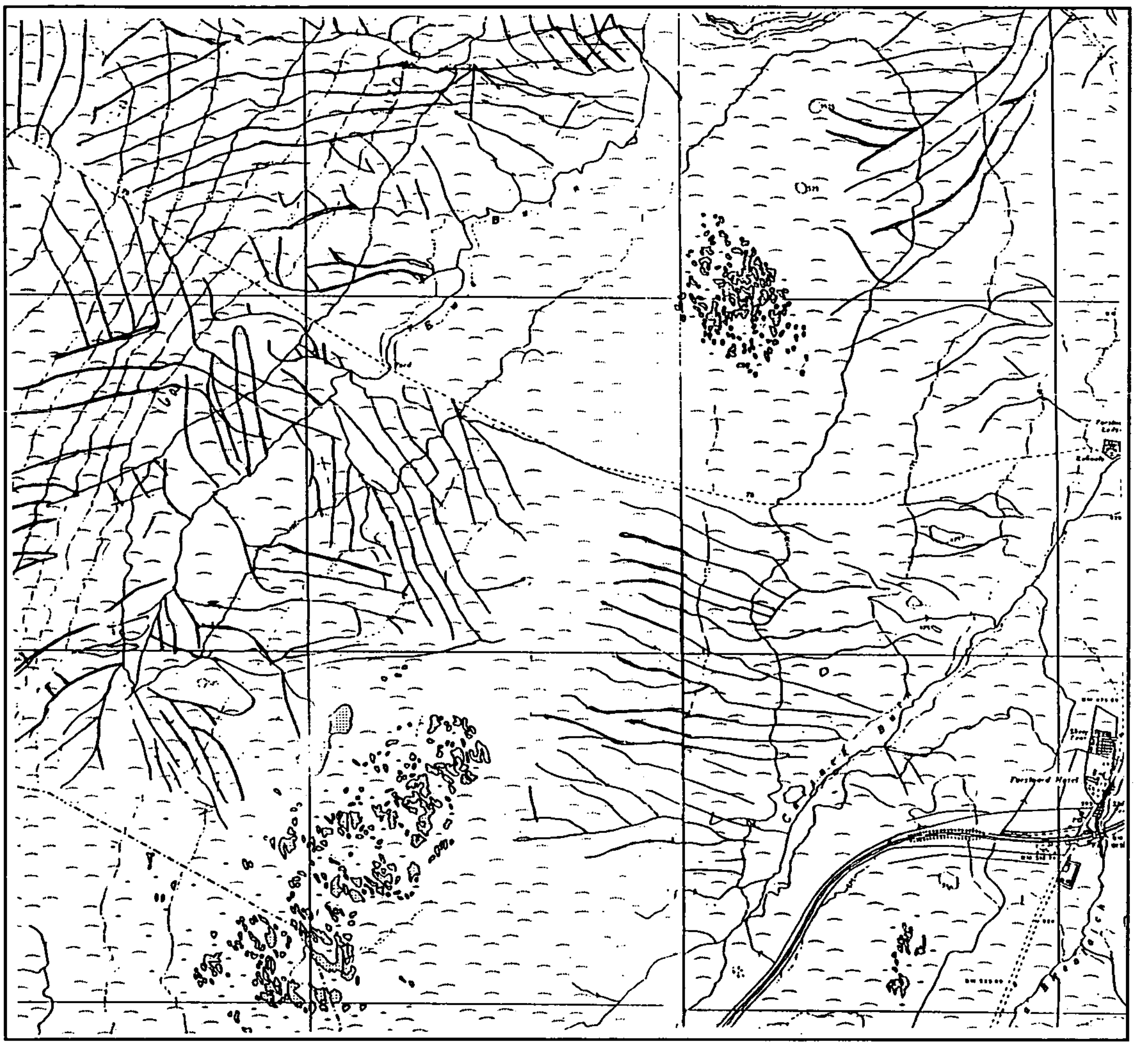

Figure 1.5: Artificial moor-gripping network on blanket peat near Forsinard, Sutherland in Scotland. Grid squares are 1 km.

Wheeler & Shaw (1995) examined drainage effects on both raised mires and blanket peat. These systems are ecologically, if not morphologically, similar so their findings are still appropriate. Therefore, much of the following is taken from Wheeler & Shaw (1995). As drainage lowers the water table there can be an accelerated decomposition of the peat, a change in the physical properties of the peat and thus the hydrology, morphology and the ecology of the peatland ecosystem are altered (Wheeler & Shaw, 1995). Typical effects are increased subsidence, bulk density and amplitude of water table fluctuation with decreases in active porosity, water content, water storage coefficient and permeability (Wheeler & Shaw, 1995). The results are primary consolidation followed by shrinkage, secondary compression and finally wastage of the upper layers of the bog (Hobbs, 1986, cited in Wheeler & Shaw, 1995). The chemistry of the peat can be altered by the induction of biochemical oxidation mineralization and the release of H+ and nutrients altering the pH. In a damaged site frequent and long periods of drought may accentuate these processes leading to a sub-optimal pH for *Sphagnum* growth. The permanence of these effects is not known.

On the vegetation, sustained lowering of the water table leads to a rise in *Calluna vulgaris* and *Molinia caerulea* and may result in invasion of birch, *Betula* spp. Long-sustained lowering of the water table can lead to loss of typical bog species and loss of the acrotelm itself leading to the aeration of the catotelm, a faster decomposition of catotelmic peat and the cessation of peat accumulation and bog growth. Vegetation effects can take a long time to become evident and in one study were confined to the downslope side of the drains (Stewart & Lance, 1991). Stewart and Lance (1991) also found that cover of species dependent on high water tables had lower cover nearer to drains, cover of *Calluna* peaked after approximately 8 years and declines in *Sphagnum* were localized and took nearly 20 years to achieve statistical significance.

The low hydraulic conductivity of the catotelm means that the effects of any one ditch are usually restricted to with a few metres either side of the ditch (Stewart & Lance, 1991). This is evident from the need to space ditches 10-20 m apart to provide sufficient drainage for the peat extraction (Wheeler & Shaw, 1995). Drainage will undoubtedly lead to a faster runoff in the immediate vicinity of the drain and long-established drains can frequently be seen to have caused lowering of the peat surface for 5-10 m creating a parabolic peat surface and thus changing the hydrology of the bog.

1.5.6 Hypothesized Effect of Drainage on the Carbon Balance of Blanket Bog

As illustrated above, the effects of drainage act on the hydrology, vegetation and physical characteristics of the peatland. None of these effects act in isolation and are likely to interact with one another. The carbon balance is likely to be affected thus:

1. Hydrology
    a. Increased run off leading to increased exports of carbon to river environments. There is some work to support this hypothesis (Yeo, 1998).
    b. Lowered water tables leading to altered exchanges of gaseous carbon through the altered decomposition processes. This may lead to lowered methane emission but increased carbon dioxide emission. The long term dynamics of this have not been explored.

2. Vegetation

    As above in section on fire and grazing.

3. Physical

    Physical effects compound both hydrological and vegetation effects and thus are likely to compound effects on the carbon balance.

1.5.7 Erosion

The most comprehensive studies of erosion have taken place in the Pennines of England by John Tallis. Although every situation could be regarded as unique and it could be argued that the Pennines may be atypical of blanket peat in the UK, the true value of these studies is that they have identified local erosion processes that have a wider applicability. Identifiable changes associated with erosion include: reduced species diversity, reduced *Sphagnum* cover, discontinuous plant cover and reduced productivity and peat accumulation (Tallis, 1997b). This led to the production of a simplified and generalized sequence of progression (see Figure 1.6 and Tallis, 1997b). Not all of these effects are displayed in any one eroded bog but this stresses the diversity of factors that are involved in the erosion process. Note the compound nature of many factors and the fact that many management practices are evident. Identified agents implicated in the erosion process are of both natural and anthropogenic origin including accidental fires of which there were 300 in the period 1970-1998 in the Peak District. At Holme Moss a particularly severe fire in 1700 is thought to be responsible for much bare peat today (Tallis, 1997b). Further agents include industrial pollution, sheep grazing, trampling, peat cutting and climatic impacts. These then may finally lead to erosion, which may take many forms from small areas of bare peat to fully formed integrated systems of gullies. Gully erosion is a feature of nearly all blanket peats in the UK and a mean erosion rate of 5.5 mm yr^{-1} has been postulated for the Peninne area indicating that a 1 m deep gully is approximately 200-250 years old with some of the deeper gullies being considerable older (Tallis, 1997b). Annual erosion rates in Shetland were 1- 4 cm yr-1 which may indicate that bare peat surfaces persist for 30-150 years for 1.5 m deep blanket peat, if erosion rates, geomorphological and management factors remain constant (Birnie, 1993). The evidence from the Pennines indicates that erosion is a long-term process. However, it may not be a permanent one: around 10% of the Moor House National Nature reserve was classified as re-vegetated former erosion (Garnett & Adamson, 1997).

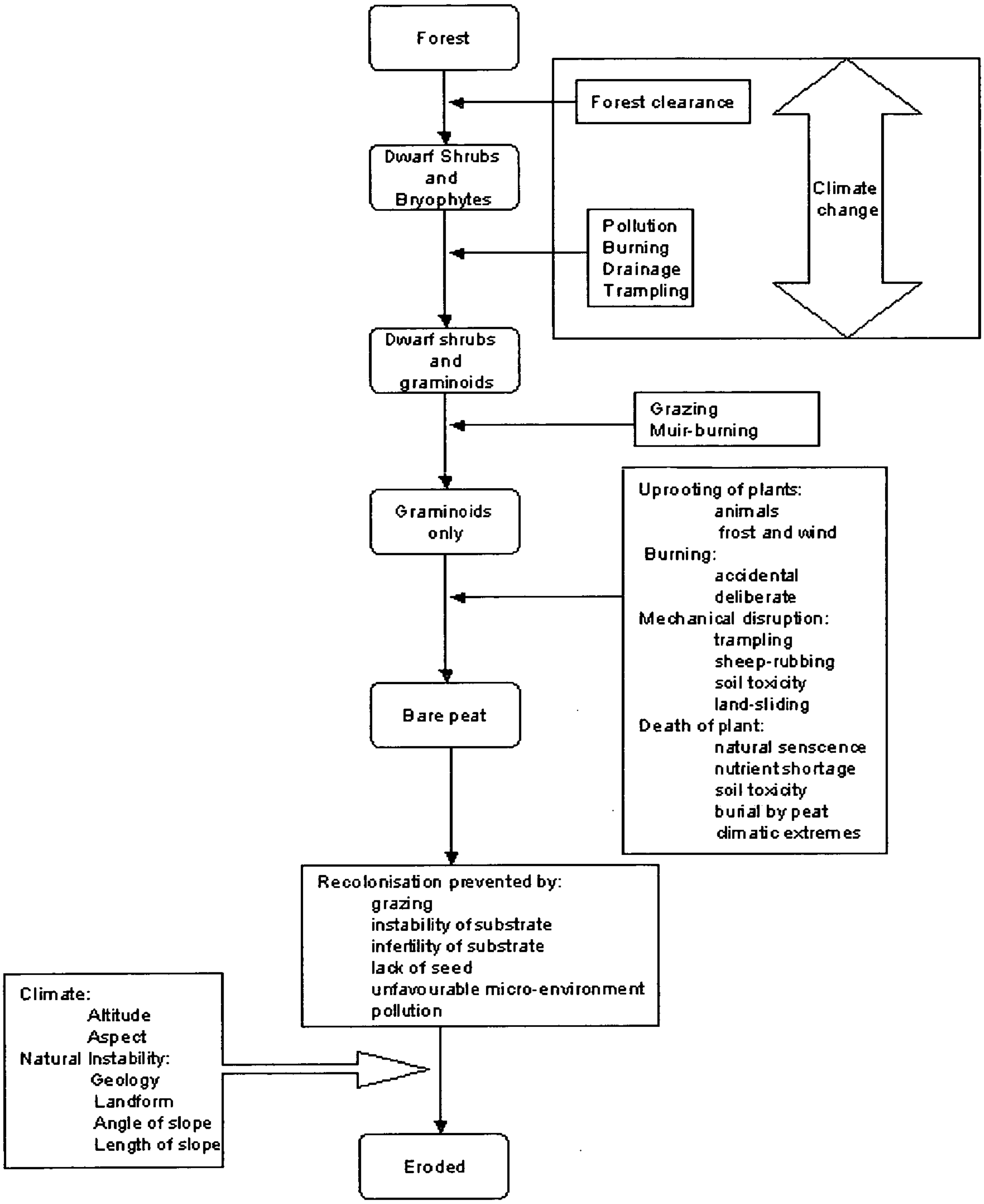

Figure 1.6: A simplified scheme of bog degradation and erosion redrawn from (Phillips, Yalden & Tallis, 1981, cited in Tallis 1998).

There is quite a body of evidence on erosion and further work can be found in the following references (Tallis, 1959, 1964, 1965; Crisp, 1966; Stewart et al., 1966;

Tallis, 1973, 1985, 1987; Bradshaw & McGee, 1988; Birnie & Hulme, 1990; Francis, 1990; Johnson et al., 1990; Stevenson et al., 1990; Birnie, 1993; Glenn et al., 1993; Heathwaite, 1993; Tallis, 1994; Tallis & Livett, 1994; Grieve et al., 1995; Tallis, 1995; Younger & McHugh, 1995; Fisher et al., 1996; Mackay & Tallis, 1996; Tallis, 1997a; Ellis & Tallis, 2000; Bragg & Tallis, 2001; Ellis & Tallis, 2001; Evans & Warburton, 2001; Wishart & Warburton, 2001; Campbell et al., 2002; McHugh et al., 2002; Waddington & McNeill, 2002; Ellis & Tallis, 2003; Warburton, 2003; Warburton et al., 2003; Warburton et al., 2004).

1.5.8 Hypothesized Effect of Erosion on the Carbon Balance of Blanket Bog

The effects of erosion on the carbon balance are likely to be very similar to the effects of drainage see above, only sometimes on a much larger scale. The carbon balance is likely to be affected as above:

1. Hydrology, as in drainage.
2. Vegetation as in grazing and burning sections.
3. Physical as in drainage section.

1.5.9 Peat Extraction

The effect of peat extraction depends entirely on the method and scale of extraction, which dictates the degree of severity to the peatland system. As noted above the majority of peat extraction in Scotland is done by domestic cutting for fuel.

1.5.10 Effect of Peat Extraction on the Carbon Balance of Blanket Bog

The use of peat as a fuel in terms of carbon is similar to other fossil fuels in that it is an unsustainable resource and emits carbon to the atmosphere. The loss of carbon due to be peat extraction was calculated as 682.92 Gg CO_2 for the year 2002 in the UK (Baggott et al., 2004). However this figure includes raised bogs and therefore the real total for blanket bog in would be less.

1.5.11 Conservation

Conservation is not strictly a management practice and the effect of designation of a site may be to introduce or cease different management practices for the achievement of the conservation goals. Conservation therefore can be assessed by reference to the different management practices presented here. In the current context the management practices of interest are those that influence the carbon balance by conserving an active bog ecosystem, i.e. a bog accumulating carbon.

1.5.12 Hypothesized Effect of Conservation on the Carbon Balance of Blanket Bog

The key here is to identify whether management by conservation is effective in conserving active status of bogs. This has yet to be assessed although SNH hold data on habitat condition for some if not all blanket bog SSSIs.

1.5.13 Restoration

Restoration could be examined under conservation but is detailed separately here because it is a fairly new practice and also due to the extensive restoration projects currently undertaken in the Caithness and Sutherland Peatlands area, where much of the field work for this thesis was conducted. Before examining the effect of restoration we need to define what blanket bog ecological restoration is, accordingly I define this as:

ecological restoration of blanket bog is defined as any management practice that is deliberately undertaken to restore ecological processes, communities and/or species to semi-natural condition, thereby enhancing the ecosystem of blanket bog.

Though broad, within this definition there are some key elements that need elaboration. A management practice that is deliberately undertaken must have the enhancement of the blanket bog ecosystem as an objective target. Further it is explicitly acknowledging that anthropogenic influence is required to achieve semi-natural status and it is also required to maintain that status (unlike definitions of naturalness for woodlands which imply naturalness without the influence of people (Peterken, 1996)). By stating that the objective is 'semi-natural condition' there is no implication that these practices can ‘turn back the clock’ and deliver any particular ecosystem that was present in the past. It is unfortunate then that the word restoration has entered into common use for conservation projects, remediation or rehabilitation may be better but since restoration is commonly used it is retained here. Finally, by including ecological processes, communities and species, this definition recognises that none of these entities exists in isolation and that they are all are required to enhance a blanket bog ecosystem.

Recent restoration in Caithness and Sutherland has concentrated on two distinct types of degraded mire: those planted with trees and those affected by moor-grips in Caithness and Sutherland. There are therefore different methods for tree removal and drain blocking, although in reality drains also need to be blocked after tree removal. Although the objectives of restoration include promotion of birds and invertebrates, the main effects examined here will be those on vegetation and hydrological impacts that primarily affect the carbon balance.

Tree Removal: In Caithness and Sutherland where the majority of the restoration projects have been carried out three methods of tree removal have been used chainsaw felling, mulcher, and mechanical tree snipper. Either, the trees are felled to waste leaving mulch behind or with cut trees and brash placed into furrows, helping to impede drainage, or the trees may be removed for use in bio-fuel or other commercial/community uses.

Drain blocking: The objective of damming drains is to raise water tables and in so doing help regulate base and peak flow rates to the respective burns, with a concomitant reduction in the frequency of spates. Outcomes are the restoration of peatland vegetation as well as hydrology. Drains are dammed, for example at 20 to 25 cm drops, either using a mixture of materials such as plastic pile and peat dams constructed by hand or using a low ground pressure digger, depending on the situation.

1.5.14 Hypothesized Effect of Restoration on the Carbon Balance of Blanket Bog

The removal of trees may result in a reduction in evapo-transpiration and hence raise the water table and promote the recovery of vegetation. The quality of the woody matter left to decay may also be important in determining the rates of decay and carbon release or retention in the newly restored acrotelm. The effects of blocking drains will be to alter the dynamics of the carbon flux in favour of methane production. As stated above it is the balance between the methane emitted and carbon dioxide fixed that is important in determining if the bog is a source or sink to the atmosphere. It remains to be seen whether the methane pulse shown by many studies (Anderson, 2001) is a transient phase and lessens over time as the vegetation becomes more established.

1.6 Examination of Policy Mechanisms for Blanket Bog Restoration

Although restoration is relatively new there is likely to be increase in restoration projects especially if policy mechanisms are used as encouragement. There is included here then a short appraisal of current policy mechanisms available to landowners that have a direct or indirect link to peatland restoration.

There are several mechanisms in place that have been used for blanket bog restoration. It also is likely that future policy mechanisms could be used for the financing of blanket bog restoration not only for specific conservation projects but also for integrated projects within the rural farming environment.

The restoration of blanket bog in the UK is a relatively recent phenomenon. It has yet to be considered on a large geographical scale. Part of the problem may be a lack of awareness of what options are available to landowners with regard to peatland restoration and the complexity of the granting system

Peatland Management Scheme (PMS - administered by Scottish Natural Heritage [SNH]): This is a scheme for SSSI landholders that include options for 'peatland restoration'. Although a very successful scheme in terms of uptake, only a few landholders have done any restoration work through this scheme. The current LIFE Peatlands Project (LPP) is trying to promote a larger uptake of this aspect of the PMS by specifying that SNH will do five restoration schemes as part of the project. The added resources of the LPP are helping SNH progress on this. All restoration work carried out to date under this scheme has been blocking hill drains.

Scottish Forestry Grants Scheme (SFGS – administered by Forestry Commission Scotland [FCS]): In June 2003 this replaced the Woodland Grant Scheme (WGS) 'Woodland Improvement Grant' that included aspects of tree removal from deep peatland. SFGS, like its predecessor, is still a restructuring grant for 'improving woodland biodiversity' with funded open-ground restoration limited to 20% of the forest area (FCS, 2003, 2005). In practice, WGS & SFGS grants are for small scale (mostly 10's of hectares) tree removal from, for example, the edge of a Natura site. In February 2005 FCS increased the rate of SFGS grant paid for open ground restoration by tree removal to 90% of 'standard costs', but the limitation of only 20% open-ground restoration of the forest remains. Going beyond 20% of forest area removed under SFGS may require a cultural shift and change in FCS's remit, with closer linkage with SEERAD/SNH and their support to manage the restored peatland. FCS may feel constrained by being the *Forestry* rather than 'Peatland' Commission.

LIFE Nature (EU): This has been the only funding source that has allowed landscape scale restoration work in peatlands. Favourable LIFE applications focus directly on the 'threats' to a Natura site. In the case of the Caithness and Sutherland peatlands these were identified as mainly hill drains and forestry. 2005 is the last year for applications for LIFE Nature projects - future funding of Natura work will come through the Rural Development Regulation 2007-2013.

Heritage Lottery Funding: The RSPB has had some success in acquiring conifer plantations on peatland areas for restoration purposes including the felling of conifer trees.

Agri-environment Schemes: These schemes have been in operation in Scotland since 1987. They are designed to encourage farmers and crofters to manage their land for the benefit of Scotland's wildlife and habitats. Participation in the schemes is for a minimum of five years. In benefiting wildlife and habitats there may also be a pay off in terms of carbon budgets particularly in the case of blanket bog where a well-managed functioning peatland is more likely to be a carbon sink than a carbon source. There are certain schemes that are no longer open for applications such as the Environmentally Sensitive Area (ESA) and Habitats Scheme, as such these schemes would not cover future peatland projects but existing agreements may still be benefiting peatland areas.

The Rural Stewardship Scheme (RSS): RSS is part of the Scottish Rural Development Plan. It replaced the Countryside Premium Scheme (CPS) and provides assistance to landowners and managers for the adoption of environmentally friendly practices and to maintain and enhance particular habitats and landscape features. The Moorland Management Option for RSS would cover elements of peatland restoration.

Organic Farming: This Scheme, which is part of the Scottish Agri-Environment Programme, came into operation in July 1994. It provides assistance to farmers and crofters who wish to convert to organic production. Although no direct payments would be made through this scheme for peatland restoration the practice of organic farming in upland areas may have an indirect benefit to peatland environments.

Land Management Contracts: The Land Management Contract (LMC) Menu Scheme was launched on 25th February 2005. The scheme for 2005 contains an option for management of moorland grazing, which aims to benefit a diverse range of habitats of conservation interest within moorland. The Menu Scheme is lower level than RSS, and does not contain prescriptions for enhancement through management. The future development of LMCs may provide further opportunities to include other aspects of peatland restoration, and the full LMC model, due to be launched in 2007, could contain further prescriptions targeted at these.

1.7 Conclusions

- Peatlands are large carbon stores.
- The largest peatland habitat in the UK is blanket bog.
- Blanket bog in the UK is subjected to varying types of management including grazing, burning.
- The geographical status of blanket bog in the UK is at present equivocal including the extent of management practices.
- Peatlands have like many other ecosystems a complex carbon cycle involving exchanges of CO_2, CH_4 and exports of organic carbon into river systems.
- Conservation of the carbon stored and carbon exchange processes of blanket bog peatlands habitat is vital for the consideration of the greenhouse gas balance of the UK.
- At present, certain peatlands may either be sinks or sources of carbon but more research is required particularly in the UK.
- Restoration of blanket bog is a relatively recent practice
- Quantification of the carbon dynamics of the UK blanket peat taking into account different vegetation composition and management regimes may reveal opportunities for the restoration of ecological processes, but whether or not peatlands can be turned into carbon sinks by ecological restoration remains to be answered.
- The only way to allow blanket bog ecosystems to adapt to climate change may be through the restoration of ecological processes.

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Chapter 2: Peatland gaseous carbon fluxes and land management: searching for a paradigm.

2.1 Introduction

Carbon flux research is important for the parameterisation of climate change models, understanding ecosystem response to climate change and informing government policy (Grace, 2004). This type of research frequently applies a bottom up approach where smaller scale research is scaled up to the landscape or higher scales (Grace et al., 2001). Meta-analysis has long been used in clinical and social science studies especially when informing wider society e.g. (Roberts et al., 2002; Altun & Arici, 2006) and is gaining in popularity in ecology (Osenberg et al., 1999; Gates, 2002) where it has recently been incorporated into a number of reviews of carbon dynamics (Peterson et al., 1999; Johnson & Curtis, 2001; Guo & Gifford, 2002; Wang & Curtis, 2002; Long et al., 2004; van Kooten et al., 2004; Manley et al., 2005; Ogle et al., 2005).

Peatland ecosystems in the boreal region store large amounts of carbon (Clymo et al., 1998) and the interactions between these ecosystems and the atmosphere are important to climate change research. The most significant greenhouse gases in terms of ombrotrophic peatlands are CO_2 and CH_4. On the other hand, N_2O appears less significant but may be more prevalent in more minerotrophic peatlands (Byrne et al., 2004). In the past few decades technological and analytical advances such as eddy co-variance have allowed the estimation of gaseous fluxes of CO_2 and CH_4 from ecosystems at fine temporal and large spatial scales (Beverland et al., 1996; Beswick et al., 1998). These have allowed informed estimates of the greenhouse dynamics of northern peatlands to be made.

Blanket bog is the most important peatland habitat and the most extensive semi-natural land habitat in the UK (Lindsay, 1995). The UK holds 10-15% of the total world area of this habitat (Lindsay, 1995) but is only approximately 0.16% of the global land mass, emphasising the importance of peatlands in the UK. The development of blanket bog is a function of past and present environmental factors (e.g. climate, geology, geomorphology) and of the nature, intensity and history of human impact (Steiner, 1997). Threats to these peatland ecosystems include drainage, agricultural improvement, burning, the effects of large herbivores, peat extraction and climate change. Peatland research in the UK has at least a century long history. However, UK peatlands have been subjected to several centuries of land management practices such as burning and grazing (Shaw *et al.*, 1996). Further, the UK's climate is oceanic and therefore climate change and ecosystem responses to climate change are likely to be different from those of the north American and European continents. Therefore, parameterisation of UK climate change models, understanding peatland response to climate change and informing government policy is likely to require a UK perspective. In this scenario a meta-analytical methodology to the analysis of peatland carbon fluxes and management would seem an ideal approach.

Here I attempt to apply a semi-quantitative approach to review gaseous CO_2 and CH_4 fluxes from UK peatlands in order to:

1. summarise previous work,
2. provide evidence of how management influences carbon fluxes in UK peatlands, and
3. indicate areas of study where research may be lacking.

2.2 Methods

Published literature on the effects of management on the gaseous carbon fluxes of blanket bog was searched using the following online bibliographic databases available through the University of Edinburgh Library:

ISI Web of Knowledge
JSTOR
INGENTA
ZETOC
Index to theses in Great Britain and Ireland

As well as the above databases keywords were also used as parameters for searches using the internet search engines Google, Google Scholar and Scirus. A list of keywords used (in various combinations) as search parameters for these databases are shown below in Table 2.1.

Table 2.1: Examples of keywords used in literature review searches.

blanket bog
bog
burn
burning
Calluna
carbon
carbon dioxide
cattle
CH_4
CO_2
deer
dissolved organic carbon
DOC
Erica
Eriophorum
erosion
fire
grazing
heath
heather
hummocks hollows etc.
mire
Molinia
moor
moor and moss
muir
muirburn
peat
peatland
restoration
Scotland
sheep
Sphagnum
UK
upland
wetland

In addition to the keywords in Table 2.1 certain authors were used in more specific searches, e.g., Clymo. The reference lists within journal papers were also investigated to identify any relevant papers. Also, of particular value for the older literature was 'Peatland Ecology in the British Isles: a Bibliography' (Field, 1981). However, it may be possible that certain references have been overlooked the main gaps are likely to be unpublished studies or reports.

There is a large array of molar and mass units reported in literature but authors do not always explicitly state which substance units pertain to, CO_2 or CO_2-C and CH_4 or CH_4-C. Unless authors have stated units, the approach adopted here is to make the assumption that when examining fluxes of CO_2 units are defined in terms of fluxes of CO_2 and when examining CH_4 they are defined in terms of CH_4. As many data points as possible were included from each study and all are given in the tables in the appendix.

2.3 Results

Table 2.2: Number and characteristics of gaseous CO_2 and CH_4 flux studies conducted in the UK from a review of papers (Clymo & Reddaway, 1971, 1972; Choularton et al., 1995; Clymo & Pearce, 1995; Fowler et al., 1995a; Fowler et al., 1995b; Nedwell & Watson, 1995; Beverland et al., 1996; Chapman & Thurlow, 1996; Fowler et al., 1996; Gallagher et al., 1996; Beswick et al., 1998; Chapman & Thurlow, 1998; Daulaut & Clymo, 1998; Hargreaves & Fowler, 1998; Lloyd et al., 1998; MacDonald et al., 1998; Moncrieff et al., 1998; Hughes et al., 1999; Freeman et al., 2002; Gauci et al., 2002; Hargreaves et al., 2003; Beckmann et al., 2004) using a keyword searches of bibliographic databases. * Note: does not necessarily sum to total number of studies because some papers used multiple methods. N/S - not stated.

Gas	No. Studies	Country	Method*	No. Sites	Bog Type	Management	Winter included
CO_2	8 3 respiration only	7 Scot. 1 Eng.	3 peat cores/lab 1 conditional sampling 3 static chamber 2 eddy covariance	6	4 blanket 2 raised	8 N/S	3 included 4 not included 2 not stated
CH_4	19	17 Scot. 1 Eng. 1 Wales	6 peat core/lab 2 conditional sampling 6 static chamber 6 eddy covariance 4 aircraft 3 vertical profile 2 tethered balloon 2 nocturnal box 2 flux gradient	11	1 raised 1 soligenous gully mire 9 blanket	19 N/S	5 included 8 not included 6 not stated

Table 2.2 summarises the work found by this review. A total of eight CO_2 studies were found but of these three were respiration only studies. There is a bias in terms of the countries studied towards Scotland with only that of Clymo and Reddaway (1971 & 1972) from England. The methodology employed is fairly evenly split between static chambers, peat cores and eddy covariance/conditional sampling. These methods have employed a variety of scales from < $1m^2$ (chambers, cores) to > $1\ km^2$ (eddy covariance). Although there are 8 studies, only 6 sites have been

sampled, therefore, some sites have been re-sampled and not always by the same authors. There are double the number of blanket bog sites (4) compared to raised bog (2) sampled. None of the studies stated the type of management of the bog and winter only appears to have been sampled in half of the studies.

A total of nineteen studies were found by this review to have examined fluxes of CH_4. Seventeen were in Scotland, one in England and one in Wales again reflecting country bias. There seem to be a larger array of methods employed and a wide variety of scales from < $1m^2$ to almost the entire north of Scotland (aircraft) (Fowler et al., 1996; Gallagher et al., 1996; Beswick et al., 1998). The numbers of sites used are again less than the number of studies indicating re-use of sites for subsequent studies. A much higher of proportion of blanket bog is represented with nine sites, with one raised bog and a soligenous gully mire also sampled. As with the CO_2 studies there is no information on site management and winter is also under represented with only five of the nineteen studies covering this season.

Table 2.3 and Figure 2.1 show mean CO_2 fluxes, standard error, mean net flux (light and dark) and sites sampled for each of the studies examined by this review. Dark fluxes range from 0.06 to 1.389 μmol CO_2 m^{-2} s^{-1} and light fluxes from -5.556 to 0.704 μmol CO_2 m^{-2} s^{-1}. The reported values give an overall mean net flux of -0.640 (se 0.925) μmol CO_2 m^{-2} s^{-1} appearing to indicate an overall sink for CO_2. Figure 2.1 also shows outlying points in grey all of which come from the study of Beverland *et al,* (1996). Figure 2.1 and Table 2.3 also indicate the paucity of studies reporting CO_2 fluxes in the light, numbering only three.

Table 2.3 Mean carbon dioxide flux results from published papers examined by this report; units are μmol CO_2 m^{-2} s^{-1}. Note; n in column 7 relates to the number of reported values from which a study mean was derived. * Value not reported.

Study No.	Reference	Site	Light Dark	Mean CO_2 flux	SE	n	Mean Net flux
1	Beckman *et al* (2004)	Ellergower Moss	Dark	0.097	0.037	3	0.082
			Light	-0.014	0.068	3	
2	Beverland *et al* (1996)	Loch More	Dark	1.389	1.389	2	-4.167
			Light	-5.556	2.778	2	
3	Chapman and Thurlow (1996)	Glensaugh	Dark	0.195	0.037	2	N/A
4	Clymo and Pearce (1995)	Ellergower Moss	Dark	0.060	0.026	2	N/A
5	Clymo and Reddaway (1971 and 1972)	Moor House Burnt Hill	Dark	0.119	0.018	3	N/A
6	Fowler *et al* (1995a)	Loch More	Dark	0.611	*	1	-0.389
			Light	-1.00	*	1	
7	Hargreaves *et al* (2003)	Auchencorth Moss	Net rate	*	*	1	-0.002
8	Lloyd et al (1998)	Ellergower Moss	Dark	0.572	0.453	2	1.276
			Light	0.704	0.557	2	
	Mean	Scottish sites	Net rate		0.925	5	-0.640

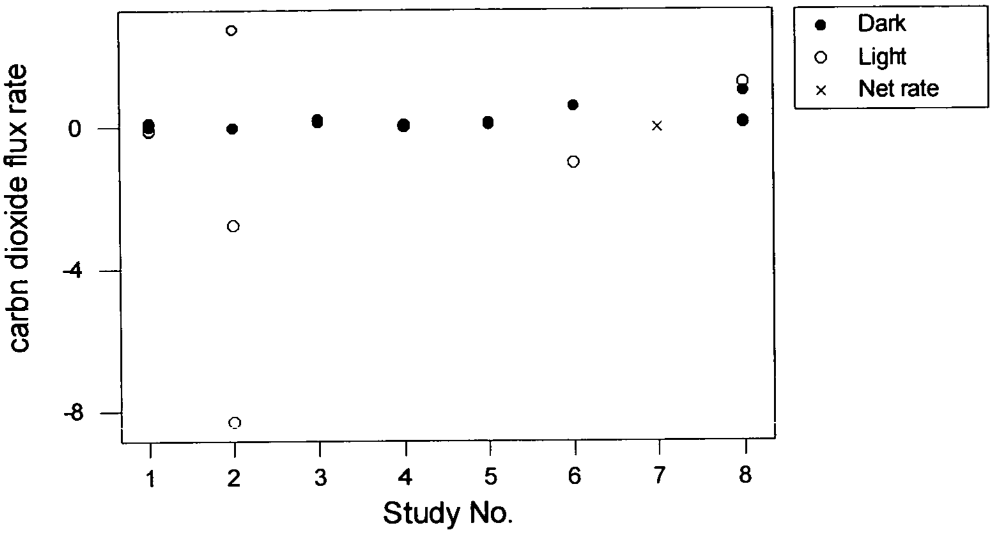

Figure 2.1: Carbon dioxide flux (μmol CO_2 m^{-2} s^{-1}) against study number from Table 11, outlying data points are shown in grey.

As there are more CH_4 studies Table 2.4 and Figure 2.2 summarise the mean CH_4 fluxes (se) by site rather than by each paper examined. What is immediately apparent from Table 2.4 is that some sites are more frequently reported than others. Loch More has eight published results, four from Ellergower Moss, three from Caithness and Strathy Bog and the rest of the sites are reported once. Values range from 0.01 μmol CH_4 m^{-2} s^{-1} at Moor House in north England to 0.131 μmol CH_4 m^{-2} s^{-1} at Cerrig-yr-Wyn in Wales. Overall mean CH_4 flux 0.029 (se 0.01) μmol CH_4 m^{-2} s^{-1}. CH_4 fluxes appear to be less prone to outliers except the values reported from Cerrig-yr-Wyn in Wales, which are high in comparison to the rest.

Table 2.4: Site mean methane flux results from published papers examined by this report; units are µmol CH_4 m^{-2} s^{-1}. Note; n in column 4 relates to the number of reported values from a site from which the mean is derived. (Clymo & Reddaway, 1971, 1972; Choularton et al., 1995; Clymo & Pearce, 1995; Fowler et al., 1995a; Fowler et al., 1995b; Nedwell & Watson, 1995; Beverland et al., 1996; Chapman & Thurlow, 1996; Fowler et al., 1996; Gallagher et al., 1996; Beswick et al., 1998; Chapman & Thurlow, 1998; Daulaut & Clymo, 1998; Hargreaves & Fowler, 1998; Lloyd et al., 1998; MacDonald et al., 1998; Moncrieff et al., 1998; Hughes et al., 1999; Freeman et al., 2002; Gauci et al., 2002; Hargreaves et al., 2003; Beckmann et al., 2004)

CH4 site	**Mean flux**	**SE**	**n**
Bad a Cheo	0.024	*	1
Caithness	0.034	0.009	3
Cerrig-yr-Wyn	0.131	*	1
Ellergower Moss	0.016	0.009	4
Loch Calium	0.014	*	1
Loch More	0.013	0.002	8
Moidach More	0.020	*	1
Moor House	0.010	*	1
North Scotland	0.013	*	1
Potree to Wick	0.014	*	1
Strathy Bog	0.032	0.023	3
Mean of all sites	0.029	0.010	11

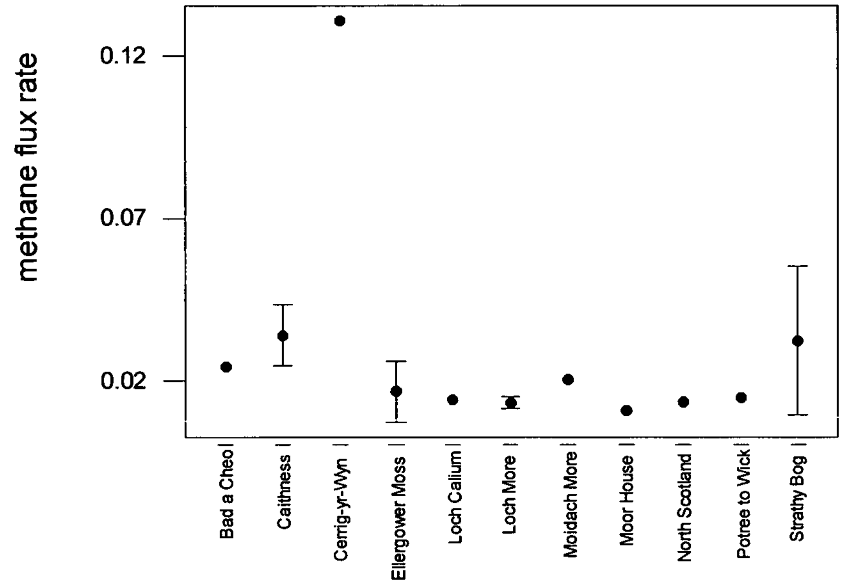

Figure 2.2: Site mean methane flux results from published papers examined by this report, units of flux are μmol CH_4 m^{-2} s^{-1}, error bars represent standard error. Site mean methane flux results from published papers examined by this report; units are μmol CH_4 m^{-2} s^{-1}. Overall mean is 0.029 μmol CH_4 m^{-2} s^{-1} (0.01).

Figure 2.3 examines some of the data from the UK peatlands where both CO_2 and CH_4 data are available, implemented in the model of Whiting and Chanton (2001). This model presents the molar ratio of CH_4/CO_2 against the molar global warming potential of methane (GWP_M) over time. The greenhouse compensation point represents a line whereby, the emission of CH_4 is balanced by the molar uptake of CO_2, and therefore, any data lying along this line is greenhouse neutral.

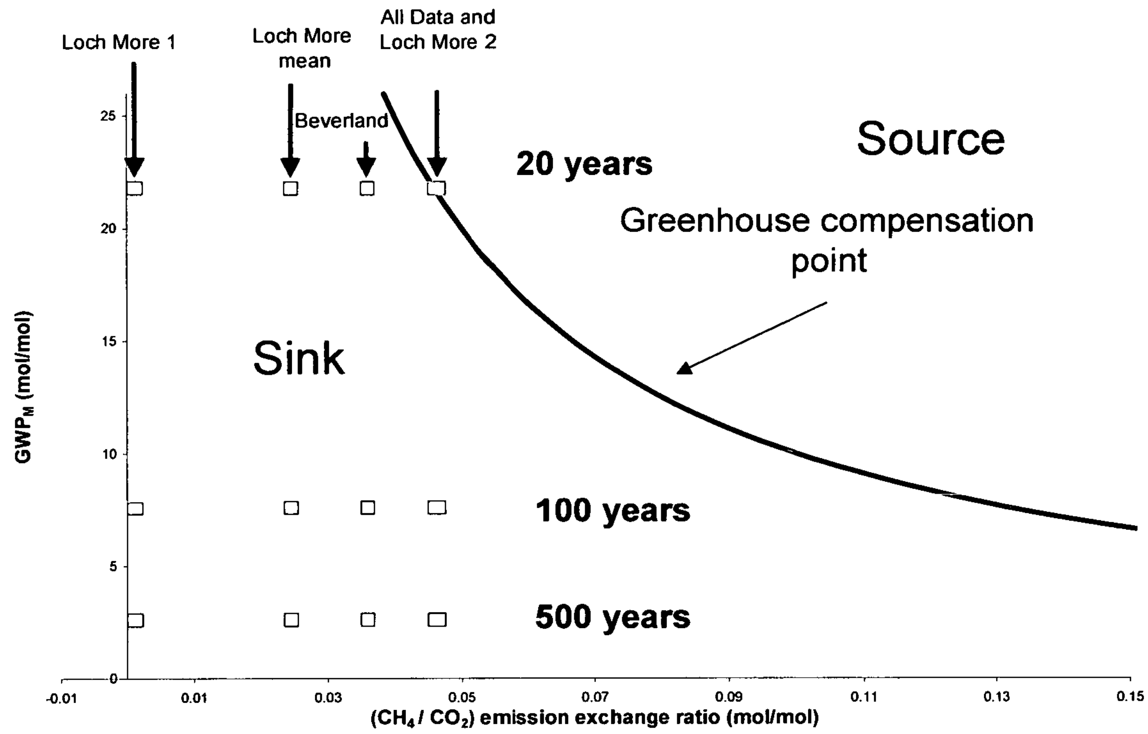

Figure 2.3: Model relating CH_4/CO_2 emission ratio to Global Warming Potential (GWP_M) and time for UK peatlands. Loch More 1 is calculated from the high and low values reported by Beverland *et al.,* (1996); Loch More 2 is calculated from Fowler *et al.,* (1995a), the Beverland ratio is calculated from reported annual sink source data (Beverland *et al.,* 1996), Loch More mean is the mean of all Loch More data, and All data represents the ratio calculated from mean all available values found in this review.

Figure 2.3 suggests that from the available data, when both CH_4 and CO_2 are taken account of, UK peats appear to be sinks for carbon in terms of global warming potential. Only the All data and Loch More 2 are marginal sinks over the 20-year scenario. However, due to the limitations of the carbon dioxide data found by this review, the results presented in Figure 2.3 can only be regarded as illustrative.

2.4 Discussion

2.4.1 Fluxes of CO_2

The evidence given above would appear to indicate that peatlands in the UK may be a sink for atmospheric CO_2 and the overall mean figure of -0.640 μmol CO_2 m^{-2} s^{-1} would seem to offer support for this. However, there are very few studies, only 8 in total, only 5 of these recorded light and dark fluxes and only 1 of these includes winter. Further, this mean is influenced by some extreme values highlighted by Figure 2.1. The extreme values reported by Beverland et al., (1996) arise because the authors reported high and low values, and the study was conducted in the height of summer when rates of exchange are at their greatest. Removing these and then recalculating the mean is unsatisfactory because the mean would then be dominated by the Ellergower Moss results of Lloyd et al., (1998) and Beckman et al., (2004). This is unsatisfactory because Ellergower is a raised bog not a blanket bog and therefore not representative of the UK peatland habitat as a whole, and these studies both reported CO_2 emissions in illuminated laboratory controlled conditions, intuitively this would appear to be unrepresentative. This would leave the reported flux of Hargreaves et al., (2003) as the only representative measure for blanket peat CO_2 flux rates. This, though, is a partly modelled value using climate data from Newton Stewart to derive a net flux rate for Auchencorth Moss approximately 130 km to the south-west not actual climate data from the site. There appears then to be no satisfactory mean value for the gaseous flux of CO_2 from UK peatlands.

2.4.2 Fluxes of CH_4

It is apparent that there is more published information on CH_4 fluxes from UK peatlands than fluxes of CO_2. From the total of nineteen studies from eleven different sites all reporting emissions of methane, an overall mean emission is 0.029 μmol (se 0.01) CH_4 m^{-2} s^{-1}. Only the values reported from Cerrig-yr-Wyn in Wales appear to be unusually large (Figure 3) but this may be due to the influence of groundwater in this slightly different habitat (soligenous mire). However, only six of the nineteen explicitly state that winter was included and this would appear to be an under represented season.

2.4.3 UK Peatlands, overall C source or sink?

Beverland et al., (1996) conclude from their results that the site would represent an annual sink of –0.5 Mt C for UK peatlands. Given the limitations of their study and the very high error variance, this is unlikely to be a reliable estimate. Hargreaves et al., (2003) give a net rate of -0.25 t C ha^{-1} yr^{-1} but this is also unlikely to be reliable because of the use of remote climate data in modelling. We must also state that the situation illustrated by Figure 2.3, and the mean values of -0.640 CO_2 m^{-2} s^{-1} and 0.029 µmol CH_4 m^{-2} s^{-1} obtained from this review, are unlikely to be reliable estimates due to the paucity of results, susceptibility to extreme values and the seasonal limitations of current research.

2.4.4 Representation of sampled sites

The country bias found in that more sites are situated in Scotland than England and Wales is expected since this is where the majority of peatlands are found in the UK (Lindsay, 1995). However, it is necessary to ask whether the sites where fluxes have been reported are representative of the entire blanket bog situation in the UK. Table 2.3 indicates that nine studies have sampled a total of 6 sites for CO_2 and Table 2.4 nineteen studies from eleven sites or areas for CH_4. Given that the blanket bog covers 1.9 million ha it is unlikely that these sites are adequate. Also two sites are raised rather than a blanket bog (Clymo & Pearce, 1995; Nedwell & Watson, 1995; Lloyd et al., 1998; Gauci et al., 2002; Beckmann et al., 2004). Although the vegetation of raised and blanket bog has similarities, the hydrologies are different and the accumulation of peat (hence carbon fixation) has been much greater historically in most raised than in blanket bogs. Even when entire geographical areas are reported using aircraft, the duration of these studies is extremely short, 1 day, with a total of 3 different days sampled in different seasons and years; 24/7/92, 3/6/93, and 29/11/94 (Fowler et al., 1996; Gallagher et al., 1996; Beswick et al., 1998). Also, the assumption that the sampling technique has adequately represented the natural variation present within the site is unlikely to have been met. Eddy co-variance is claimed to report average emissions representative of areas of km^2, however, it should be remembered that the sample size in eddy-covariance studies is usually 1 tower, in other words there is no replication; there is therefore a reliance on technology to deliver accurate results with no estimation of spatial variation or precision. Chamber or peat core studies on the other hand usually have much higher replication but cover areas of usually less than 1 m^2. Monolith and peat core studies are further complicated by disturbance and the fact that they are usually conducted in the laboratory, i.e. not in the climatic condition in which they were found. Therefore, present gaseous carbon flux research on peatlands in the UK cannot be regarded as representative at local, regional or national levels.

2.4.5 Management

As one of the primary objectives of this review was to examine carbon fluxes in relation to management it is disappointing to report that none of the research examined during this review stated site management. It is therefore not possible to apply a full meta-analysis investigation into the effects of management on gaseous carbon flux at present. However, there has been some recent carbon accumulation peat core work on a long-term burning and grazing experiment at Hard Hill, on the Moor House NNR in the Pennines in England (Garnett, 1998; Garnett et al., 2000). The Hard Hill experiment is a split plot design with three burning treatments not burnt since 1954, a 10-year burn rotation and a 20-year burn rotation. These are then split between grazed and ungrazed plots. This experiment has been running since the 1954 and although Garnett *et al.,* (2000) did not examine all treatments, they conclude from the core data that burning on the 10 year rotation has an adverse effect on carbon accumulation, but there was no detectable effect of grazing probably due to the low stock rates at Moor House. However, as peat cores integrate peat accumulation over longer periods it is difficult to compare this type of data in terms of gaseous flux data.

The reasons for the lack of management details may firstly be because the primary goals of the studies were not to examine management. However, given that all the peatlands in the UK are managed to varying extent (see Chapter 1) it would seem amiss not to include even a cursory description of site management. This would be more difficult for the larger scale aircraft studies but should not be a problem for the smaller scale methods of chambers, peat cores and eddy covariance. It is only possible to speculate on further reasons for this omission but there may also be a misguided view that there are peatlands in the UK that are not managed and can be described as 'pristine'. Hargreaves et al., (2003) clearly describe Auchencorth Moss in the Scottish Borders as an undisturbed peatland; highly unlikely for a site a few miles from the capital of Scotland and nestled in an area long populated and exploited for agriculture Gauci et al., (2002) describe the raised bog sampled as 'pristine' again this is highly unlikely given that raised bogs are some of the most exploited peatland habitats in the UK. Although gradations in habitat condition undoubtedly exist, the existence of unmanaged peatlands in the UK is questionable. Nevertheless, future carbon flux research in the UK should include descriptions of management even if this is not the primary goal of the research not only to allow adequate evaluation of results but also to allow future reviews to compile results in terms of management.

2.4.6 Climate change: models, ecosystem response and government policy

As the information available on gaseous carbon flux data in the UK is sparse, it would seem prudent to ask what options are available if data are to be incorporated into climate change models, or for informing ecosystem response, or even informing government policy. Given the evidence presented in this review it would seem the options are limited to either extrapolation beyond the bounds of the studies or collation of fluxes from other areas such as Canada or Scandinavia. Both extrapolation and collation of fluxes from other areas are undesirable for the following reasons.

Extrapolation to arrive at estimates for fluxes of CO_2 and or CH_4 from present data for UK peatlands requires the acceptance of unrealistic assumptions. As detailed above currently spatial and temporal variation are all inadequately represented. This extrapolative approach then would require further research. This may be compounded by the insistence of some funding bodies and some editorial policy that requires research to be novel, this is at odds with attaining the goal of adequate representation, since it leads to the proliferation of quasi-replicated studies and experiments (Palmer, 2000) instead of the required 'true' replication through space and time.

The use of data from others areas would seem the only sensible option at present but is also undesirable because firstly as stated above the UK has an oceanic climate unlike the more continental climate of other areas. Further, permafrost studies are not applicable in the UK as the UK does not have any permafrost peatlands and the responses of these systems are likely to differ because predicted temperature rises are believed to be more extreme in more northerly latitudes (IPCC, 1996). Therefore the amplitude of permafrost boundary variation is likely to have more profound consequences on CO_2 and CH_4 emissions than those from UK peatlands from predicted climate scenarios. Most importantly, unlike continental peatlands and other northern boreal peatlands UK peatlands have been subjected to deliberate management practices for many centuries and consequently UK peatland ecosystems are in no way pristine or undisturbed. The peat in the UK may therefore differ not only biologically but also physically from those on the continent because of the history of these management practices. This may have important consequences. It is therefore important that future carbon flux research in the UK addresses management issues.

2.4.7 Peatland carbon flux research: a global context

The UK may only be approximately 0.16% of the terrestrial biosphere but 10-15% of the total world area of blanket bog is located in the UK (Lindsay, 1995). Historically the UK has made important contributions to gaseous flux research. Indeed Clymo and Reddaway (1971 & 1972) made what may have been the first ever attempt at quantifying CH_4 fluxes at Moor House. The TIGER programme provided continuity through to the late 1990's on peatland research and gaseous carbon fluxes in the UK (Oliver et al., 1998). This initial impetus appears to have lapsed in the UK at least for peatland ecosystems, although the Scottish Executive are funding an organic soils modelling project. In other areas such as the north American and European continents peatland gaseous flux research has continued and have helped to elucidate the relationships between environmental controls, the impacts of forestry, drainage and restoration on gas fluxes in peatlands (Billings et al., 1982; Crill et al., 1992; Dise, 1992; Martikainen et al., 1992; Oechel et al., 1993; Whiting & Chanton, 1993; Bubier, 1995; Christensen et al., 1996; Waddington et al., 1996; Bridgham et al., 1999; Christensen et al., 1999; Joabsson et al., 1999; Komulainen et al., 1999; Tuittila, 2000; Aurela et al., 2001; Aurela et al., 2002; Blodau, 2002).

The importance of CH_4 fluxes from peatlands to the global carbon budget is well evidenced (Gorham, 1991). There are strong links between water table and vegetation on CH_4 fluxes, CH_4 is oxidised in the acrotelm and research examining the links between water table and vegetation have shown some peatland types to be sinks and others sources (Bubier et al., 1995; Clymo & Pearce, 1995). Although techniques for measuring continuous CO_2 have been used for a while, techniques for the continuous measurement of CH_4 are only just becoming cost effective and more widely available. Previously campaign measurements were possible (Beverland et al., 1996). Now tunable diode lasers (TDL) are available that make fast automatic measurements, so that CH_4 can be measured by eddy covariance. This kind of research will be vital to complement the CO_2 eddy covariance work and elucidate management relationships in peatlands. Further CH_4 research is also required to help clarify recent controversy showing that plants even when aerobic, emit methane (Keppler et al., 2006). However the findings remain controversial and are lacking in a biological explanation. What is clear is that there is a continuing and fast developing research base in which the UK appears to be at present lagging behind.

2.5 Conclusions

Current research does not allow adequate estimation of gaseous carbon fluxes from peatland ecosystems in the UK. Also the influence of management of gaseous carbon fluxes is lacking. There is an urgent need for further research not only to address this but also to address the lack of spatial and temporal evidence. This has implications for UK climate change models, UK peatland ecosystem response to climate change and UK government policy. Finally research opportunities exist for the elucidation of disturbance effects on peatland gaseous fluxes on large scales that have implications on global carbon dynamics due to emerging technology.

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Chapter 3: Blanket Bog Site Characteristics and the Role of Management

3.1 Introduction

Determinants of blanket bog vegetation are climatic (Moore & Bellamy, 1974; Lindsay et al., 1988; Lindsay, 1995) and anthropogenic. There is some evidence that human destruction of forest since the last glaciation led to the formation of blanket bog in some areas (Moore & Bellamy, 1974; Jacobi et al., 1976; Moore et al., 1984; Tallis, 1991; Moore, 1993) and there are demonstrable links between modern anthropogenic management and blanket bog vegetation (Chapter 1). There are likely to be interactions between management actions and climate. Therefore, if we are to understand ecosystem response to climate change or the effect of ecosystems on the climate system, then the implications of management actions on that ecosystem need to be understood. Further, if we are to mitigate for any negative consequences on the climate through management practice resulting in a positive global warming potential, then it is only through changes to management that this can be redressed. The UKCIP02 report predicts warmer winters and drier summers (Hulme et al., 2002) if these predictions are realised then these will impact on the vegetation of blanket bog. Management practices such as burning and grazing have been practiced on UK peatlands for centuries (Chapter 1). Therefore an understanding of the impacts of management is vital for predictions of climatic change vegetation response.

3.2 Study aims

Here data from northern England and the north of Scotland are used to explore how management affects the vegetation of blanket bog. Management is investigated through vegetation survey of a replicated split plot management experiment and sites with gradations in regular management practices. Attempts are made to separate out innate site characteristics from those identifiable to management. The implications of management on carbon fluxes are explored in Chapter 5.

3.3 Methods

3.3.1 Site Descriptions

3.3.1a Moor House

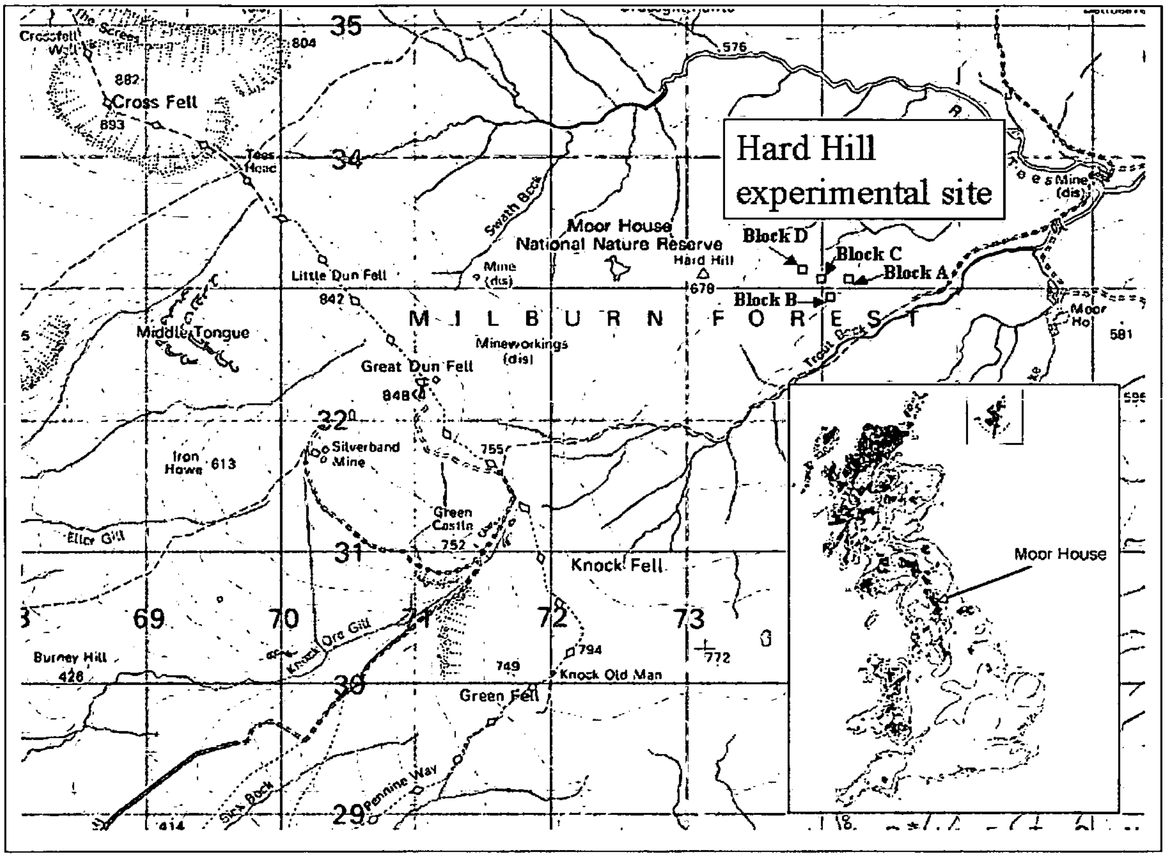

Figure 3.1: Locations of Hard Hill experimental plots and location of Moor House in the UK with peat over 50 cm marked as black (inset adapted from Lindsay 1995). Map reproduced by kind permission of Ordnance Survey © Crown Copyright.

Moor House is situated in the Northern Pennines (Grid Ref NY 757 328), has an area of 74 km^2 and ranges in altitude from 290 to 850 m asl. It is a large part of the catchment of the River Tees and a National Nature Reserve (NNR), a UNESCO Biosphere Reserve and a European Special Protection Area. The site includes exposed summits, extensive blanket peatlands, upland grasslands, pastures, hay meadows and deciduous woodland. Moor House has history of scientific research stretching back to the early 1950's and has a number of long-term experiments including investigation of management on blanket bog at Hard Hill. This is a split block, burning and grazing experiment established 1954. The Hard Hill site is located on blanket peat of approximately 1-2 m depth, mean annual rainfall is approximately 1900 mm with mean temperature of 5.1 °C (Heal & Smith, 1978).

Figure 3.1 and Table 3.1 detail location, vegetation and management of the Moor House and the Hard Hill site. The entire study area was burned prior to the construction of the experimental blocks in 1954 and the method used, was and still is, similar to traditional moorland burning (Hobbs & Gimingham, 1987). The site is arranged as in Figure 3.2 with four blocks two grazing treatments, grazed and ungrazed and three burning regimes; 0 burn (burnt in 1954 only) 10 year and 20 year rotational burning. Grazing is light with approximately 0.02-0.2 ewes per hectare (Smith & Forrest, 1978).

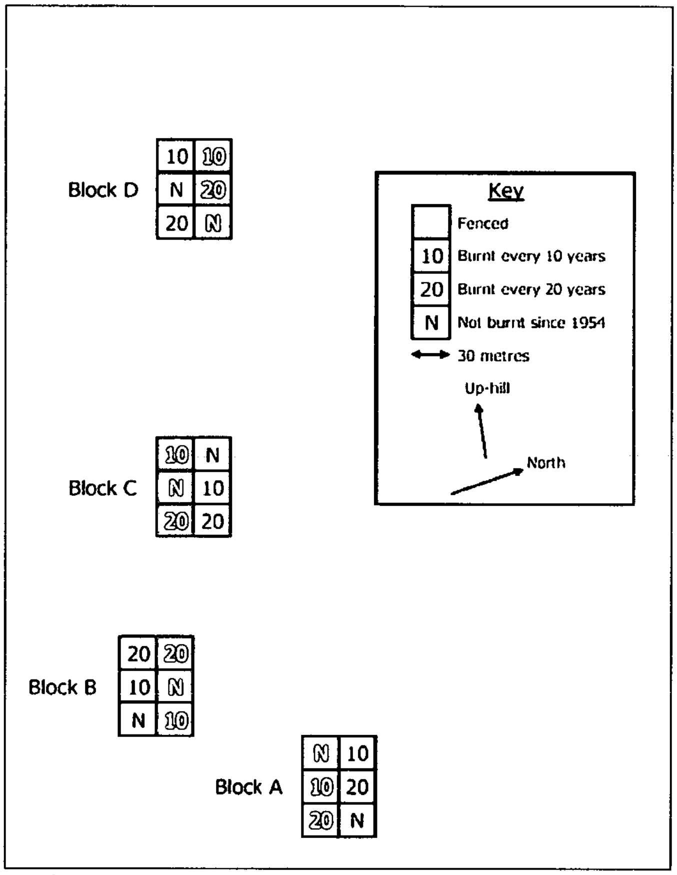

Figure 3.2: Details of Hard Hill experimental set up (Adamson & Kahl, 2003).

3.3.1b Forsinard

The Forsinard and Dorrery RSPB Nature Reserve (Grid Ref NC 905 465) is located in Sutherland, Scotland and covers an area of 112 km^2 and ranges from 44 to 580 m above sea level (asl), with most of the deep peatlands between 120 and 438 m asl. Field-work was conducted at a total of nine ombrotrophic blanket bog sites between Grid Ref NC 83 45 in the west and NC 97 45 in the east (Figure 3.3). Location and management details of each of these sites are given in Table 3.1. The climate of the area is characterised by high and frequent rainfall with annual amounts in the region of 1000-1500 mm yr^{-1} with approximately 160 - 180 wet days yr^{-1} (a 24 hour period where over 1 mm rainfall is recorded) (Lindsay et al., 1988). Mean daily temperatures are in the region of 8 ^{o}C. The reserve lies in a bioclimatic region considered to be Euoceanic, very humid, southern boreal and lower oroboreal and the major area of peat formation in the flow country conforms to this classification (Birse, 1971, cited in Lindsay et al., 1988). The reserve forms part of the Peatlands of Caithness and Sutherland, an internationally important peatland habitat recognised by status as a Ramsar site, Special Protection Area (SPA), candidate Special Area of Conservation (SAC) and proposed World Heritage Site.

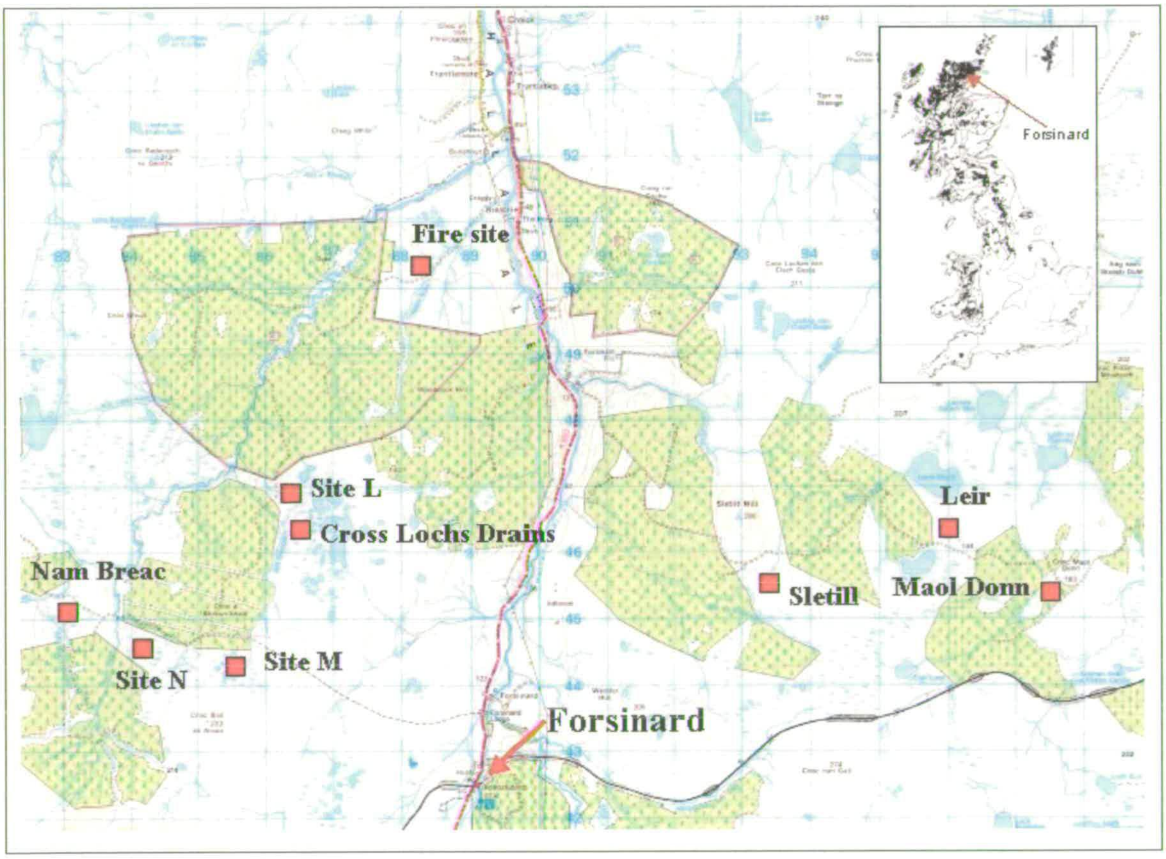

Figure 3.3: Locations of sampling sites in relation to Forsinard Sutherland and location of Forsinard in the UK with peat over 50 cm marked as black (inset adapted from Lindsay 1995). Map reproduced by kind permission of Ordnance Survey © Crown Copyright.

Table 3.1: Details of Hard Hill Site at Moor House NNR and the 11 sampling sites located within the Forsinard Reserve. Determination of National Vegetation Communities (NVC) (Rodwell, 1991) was aided by the use of ComKey computer software (Legg, unpublished). All NVC communities constitute Biodiversity Action Plan (BAP) priority habitats under present JNCC guidelines. Low Med High Deer inferred from an RSPB survey of animal footprints see Appendix. *NVC of vegetation derived from Calluneto - Eriophoretum (Eddy et al., 1969)

Site	Grid Ref	Alt (m a.s.l.)	NVC Community/sub-community	General management and site characteristics
Hard Hill:			*M19b Calluna vulgaris Eriophorum vaginatum blanket raised mire/Empetrum nigrum sub community	Nature conservation, experimental plots with grazing and burning treatments.
Block A	NY 743330	600-630		
Block B	NY 740330			
Block C	NY 736330			
Block D	NY 738331			
Nam Breac	NC 831 451	190	M17b Scirpus cespitosus Eriophorum vaginatum mire/Cladonia sub community	Nature conservation, high deer. Bare peat evident throughout site
Sletill	NC 933 456	185	M17a Scirpus cespitosus Eriophorum vaginatum mire/Drosera-Sphagnum sub community	Nature conservation, low deer. Relatively intact site
Leir	NC 958 461	195	M17a Scirpus cespitosus Eriophorum vaginatum mire/Drosera-Sphagnum sub community	Nature conservation, low deer. Relatively intact site though some bare peat present
Maol Donn	NC 975 454	165	M18a Erica tetralix Sphagnum papillosum raised and blanket mire/Sphagnum magellanicum - Andromeda polifolia sub community	Nature conservation, low deer. Relatively intact site
Fire Site	NC 881 501	105	M15 Scirpus cespitosus Erica tetralix wet heath	Not within reserve boundary, open for sheep and deer stalking. Fire burnt early 2004, burnt and unburnt areas within the same site
Site L	NC 861 467	180	M17a Scirpus cespitosus Eriophorum vaginatum mire/Drosera rotundifolia Sphagnum spp. sub community	Nature conservation, low deer. Bare peat evident throughout site
Site M	NC 856 444	220	M17a Scirpus cespitosus Eriophorum vaginatum mire/Drosera rotundifolia Sphagnum spp. sub community	Nature conservation, high deer. Bare peat evident throughout site
Site N	NC 843 447	180	M17a Scirpus cespitosus Eriophorum vaginatum mire/Drosera rotundifolia Sphagnum spp. sub community	Nature conservation, high deer. Bare peat evident throughout site
Cross Lochs Drains	NC 864 465	180	M17a Scirpus cespitosus Eriophorum vaginatum mire/Drosera-Sphagnum sub community	Nature conservation, med deer. Drained site, blocked and unblocked drains sampled. Drains cut in the 1970's and 80's and blocked 1/08/96

Table 3.2: Number of relevés per site and dates of vegetation sampling from Forsinard sites 2004-2005.

Main Site	Site	No. vegetation relevés	Vegetation sampling dates
Moor House	Hard Hill	3 per plot 18 per block	May 2002
Forsinard Reserve	Nam Breac	20	July – Aug 2004
	Sletill	20	July – Aug 2004
	Leir	20	July – Aug 2004
	Maol Donn	20	July – Aug 2004
	Fire	15 burnt 15 unburnt	Aug 2004
	Site L	20	July – Aug 2004
	Site M	20	July – Aug 2004
	Site N	20	July – Aug 2004
	Cross Lochs Drains	15	July 2005

3.3.2 Vegetation Characterisation

Field-work began at Moor House in May 2002 and at Forsinard in July 2004, details of sampling dates are given in Table 3.2.

3.3.2a Moor House

In each of the split plots three random, 0.32 m^2 relevés (same area as gas flux chambers, see Chapter 4) were sampled. The visual percentage cover of all species including vascular plants, bryophytes, macro-lichens and bare peat was recorded.

3.3.2b Forsinard

Vegetation sampling began in July 2004 and was initially completed in August 2004 except for the Cross Lochs Drain site, which was sampled in June of 2005. At each site the vegetation composition and structure was recorded in the following way:

- The visual percentage cover of all species including vascular plants, bryophytes, macro-lichens and bare peat was recorded from relevés as above.
- Deer, sheep and hare, faecal count by species within relevés.
- Deer and sheep footprint count by species within relevés.

- Vegetation canopy height and structure, using the percent obscured stick method, which is as follows: A stick marked with bands of 2 cm was placed at nine points in the relevé in a 3 x 3 grid. The height of the moss layer and any other species touching the stick and within 5 cm of the stick, are recorded with the stick held vertically at arms length. The visual percentage of the stick that is obscured by the vegetation in each 2 cm band is then recorded.
- Site surface (< 10 cm) pH was measured with 15 replicates per site.
- The Bush recording soil penetrometer (Campbell & O'Sullivan, 1991) was used for pressure readings at every 1 cm to a depth of 50 cm, with 50 insertions per site except at the Cross Lochs Drains. Penetrometer readings at the Cross Lochs Drains were taken from five 10 m transects from unblocked and blocked drains insertions were at 0.5m and every metre from 1 –10 m.

3.3.3 Statistical Analysis

Vegetation data were analysed using Detrended Correspondence Analysis (DCA) and vegetation and environmental variables with Canonical Correspondence Analysis (CCA) and Redundancy Analysis (RDA). DCA, CCA and RDA were implemented in Canoco 4.5 software. The percent obscured stick method data were analysed to give indices of shrub biomass, canopy height, density and heterogeneity (G. M. Davies unpublished) using PObscured computer software (Legg, unpublished). PObscured calculates the logit regression of the percentage obscured in each band against height, means and standard deviations are then computed for each quadrat from the nine stick observations. The calculated indices are as follows (Legg, unpublished):

- 10% height and 50% height. The height on the stick at which 10% and 50% of the particular band is obscured. These data are obtained by fitting the logistic curve to the data and interpolating (or extrapolating) from the smoothed curve. These data should be more robust measures of canopy height (though 50% can be negative for very thin crowns) than simple height measurements as these are more variable and prone to extreme values.
- Volume. Volume is the area between the fitted curve and zero height. It is called 'volume' because it is derived from a height times an area (%

obscured). It is used as an index of biomass and may be expected to give good correlation although this has yet to be confirmed in vegetation other than Callunetum (G. M. Davies unpublished).

- Intercept and Slope: These are the intercept and slope of the logistic regression of percent obscured on height. The intercept is the logit of percent obscured extrapolated to the base of the stick reflecting light penetration to ground level, and the slope is the increase in logit (percent obscured) per cm increase in height reflecting canopy density.

3.3.4 Community comparison

Comparison of vegetation data with the NVC and the communities of the Moor House reserve (Eddy et al., 1969) was done using ComKey (Legg, Unpublished). The communities of Eddy et al., (1969) included in this analysis are the Calluneto-Eriophoretum Typical facies, Calluneto-Eriophoretum *Sphagnum recurv*um facies, Calluneto-Eriophoretum *Empetrum nigrum* facies, Calluneto-Eriophoretum Burnt facies, Trichophoretum-Eriophoretum typical facies and Eriophoretum high level facies. The Calluneto-Eriophoretum community is considered synonymous with M19 *Calluna vulgaris-Eriophorum vaginatum* blanket mire, the Trichophoretum-Eriophoretum typical facies with M18 *Erica tetralix Sphagnum papillosum* raised and blanket mire and Eriophoretum high level facies synonymous with the M20 *Eriophorum vaginatum* blanket and raised mire, NVC communities (Rodwell, 1991). Eddy et al., (1969) originally mapped the Hard Hill site as the Calluneto-Eriophoretum burnt facies.

Two approaches are used, firstly simple classification of treatments to a community by reference to Rodwell (1991) and using the Czekanowski similarity coefficient, commonly used by vegetation consultants using e.g. MAVIS (Smart, 2000). Secondly by deriving a Presence-Weighted Similarity (PWS) and Sørensen Similarity coefficients for relevés to data from Eddy et al., (1969) and tabulated NVC samples and then analysed using Principal Components Analysis (PCA). Communities selected for use in PCA were those that matched with a similarity of greater than 50 using PWS. The Czekanowski, PWS and Sørensen coefficients are defined as (Legg, unpublished):

$$\text{Czekanowski} = 2\ b_m\ /\ (S+C)$$

where:

b_m = minimum of the abundance in the sample and community

S = number of species in sample

C = number of species in community

$$\text{PWS} = (\text{sum}\ (b_p)\ /\ 5*S) * 100$$

where:

b_p = community presence values of species occurring in both relevé and community, and S = number of species in relevé.

$$\text{Sørensen} = 2\ B\ /\ (S+C)$$

where:

S = number of species in sample

C = number of species in community

B = number of species that occur in both sample and community

Czekanowski is a symmetrical coefficient that assumes that the sample and the type community are equivalent in every way. Thus the match will tend to be biased towards species-poor type communities that have a similar total number of species to the sample. Similarly, it is not appropriate to compare cover-abundance scores of the sample with presence classes of the type and is not therefore suitable for single relevé data.

PWS is the sum of NVC community table frequency values (1-5) for only species that occur in both the relevé and the community, divided by 5 multiplied by the number of species in the relevé, multiplied by 100. This will give 100 for community containing all S species with presence class 5, or 20 for all species present with presence class 1. The score is thus heavily weighted towards the most frequent species.

> Sørensen is a symmetrical coefficient that assumes that the sample and the type community are equivalent in every way. Thus the match will tend to be biased towards species-poor type communities that have a similar total number of species to the sample.

All other summary statistics and graphical plots were generated using Minitab 13 and Microsoft Excel 2000 software.

3.4 Results

3.4.1 Moor House

Table 3.3 shows the species recorded from a total of seventy two relevés in the vegetation survey of Hard Hill, number of relevés for each species in each treatment and species codes for ordination diagrams. There are a total of twenty-five species that include nine vascular plants, nine mosses, three liverworts and four lichens. All species are common to mire and heathland habitats, none restricted or rare in the UK.

Table 3.3: Species, Species code, and total number of relevés in each treatment for each species recorded from a total of 72 relevés sampled from Hard Hill experimental site, Moor House NNR. Species are arranged in order of abundance in terms of the total number of relevés they are present in.

Species	Species code	Grazed	Ungrazed	0 burn	10 yr	20 yr
Calluna vulgaris (L.) Hull	Call vul	36	35	24	23	24
Eriophorum vaginatum L.	Erio vag	34	35	24	24	21
Eriophorum angustifolium Honck.	Erio ang	30	23	11	18	24
Dicranum scoparium Hedw.	Dic scop	24	19	9	16	18
Rubus chamaemorus L.	Rub cha	21	18	15	14	10
Hypnum jutlandicum Holmen & E.Warncke	Hyp jut	14	12	21	2	3
Sphagnum capillifolium (Ehrh.) Hedw.	Sph cap	10	13	5	13	5
Calypogeia muelleriana (Schiffn.) Müll.Frib.	Caly mue	15	7	-	12	10
Empetrum nigrum subsp. *nigrum* L.	Emp nig	7	13	9	7	4
Polytrichum commune Hedw.	Poly com	8	11	-	12	7
Plagiothecium undulatum (Hedw.) Bruch, Schimp. & W.Gümbel	Plag und	8	11	11	2	6
Lophocolea bidentata (L.) Dumort.	Loph bid	7	11	3	6	9
Cladonia portentosa (Dufour) Coem.	Clad imp	5	6	8	2	1
Pleurozium schreberii (Brid.) Mitt.	Pleu sch	5	4	8	-	1
Aulacomnium palustre (Hedw.) Schwägr.	Aula pal	-	6	3	2	1
Mylia taylorii (Hook.) Gray	Myl tay	3	3	0	3	3
Vaccinium vitis-idaea L.	Vacc vit	2	3	2	3	-
Cladonia chlorophea (Flörke ex Sommerf.) Sprengel.	Clad chl	1	4	2	2	1
Vaccinium myrtillus L.	Vacc myr	2	3	1	4	-
Cladonia sp.	Clad sp	1	2	1	1	1
Dryopteris dilatata (Hoffm.) A. Gray	Dry dil	1	1	-	-	2
Rhytididelphus loreus (Hedw.) Warnst.	Rhy lor	-	2	2	-	-
Hypogymnia physoides (L.) Nyl.	Hyp phy	1	1	1	1	-
Sphagnum fallax (H.Klinggr.) H.Klinggr.	Sph rec	1	0	-	1	-
Trichophorum cespitosum (L.) Hartm.	Trich ces	1	0	-	-	1

Figure 3.4 and 3.5 show sample and species plots of a DCA using the Hard Hill vegetation data. The longest gradient length is 2.8 and axes 1 and 2 account for 17.2 % and 10.9 % of the variation in the vegetation data, where as the 3rd and 4th axes account for 8 and 6.7 % respectively. Sample 36 is an outlier due to the abundance of *T cespitosum* removing this sample gives gradient length of the first axis is for 3.1 and axes 1 and 2 account for 16 % and 10.6% of the variation in the vegetation data and the 3rd and 4th axes account for 6.9 and 5.1 % respectively. The gradient lengths are relatively short and therefore linear techniques such as RDA are appropriate (Lepš & Šmilauer, 2003).

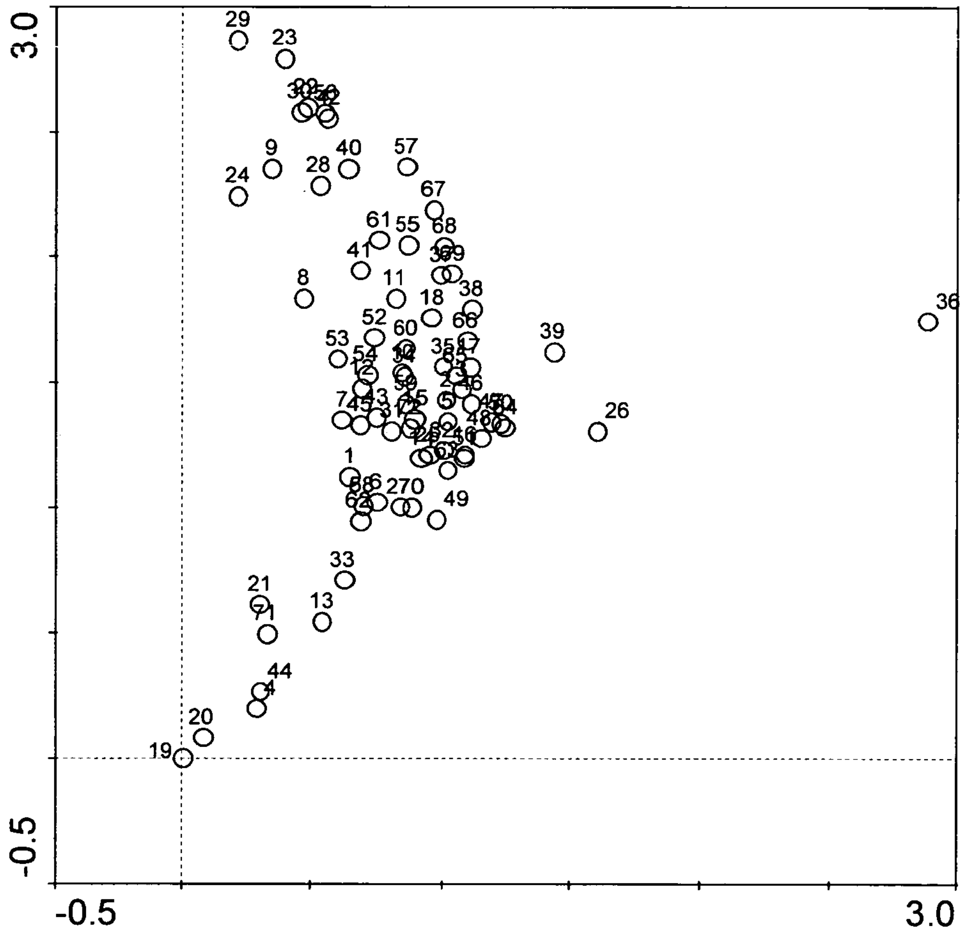

Figure 3.4: Axes 1 and 2 of a DCA of species percentage cover data showing samples from Hard Hill. Plot codes are as in Table 3.3. Axes 1 and 2 accounted for 17.2 % and 10.9 % respectively of total variation in vegetation data.

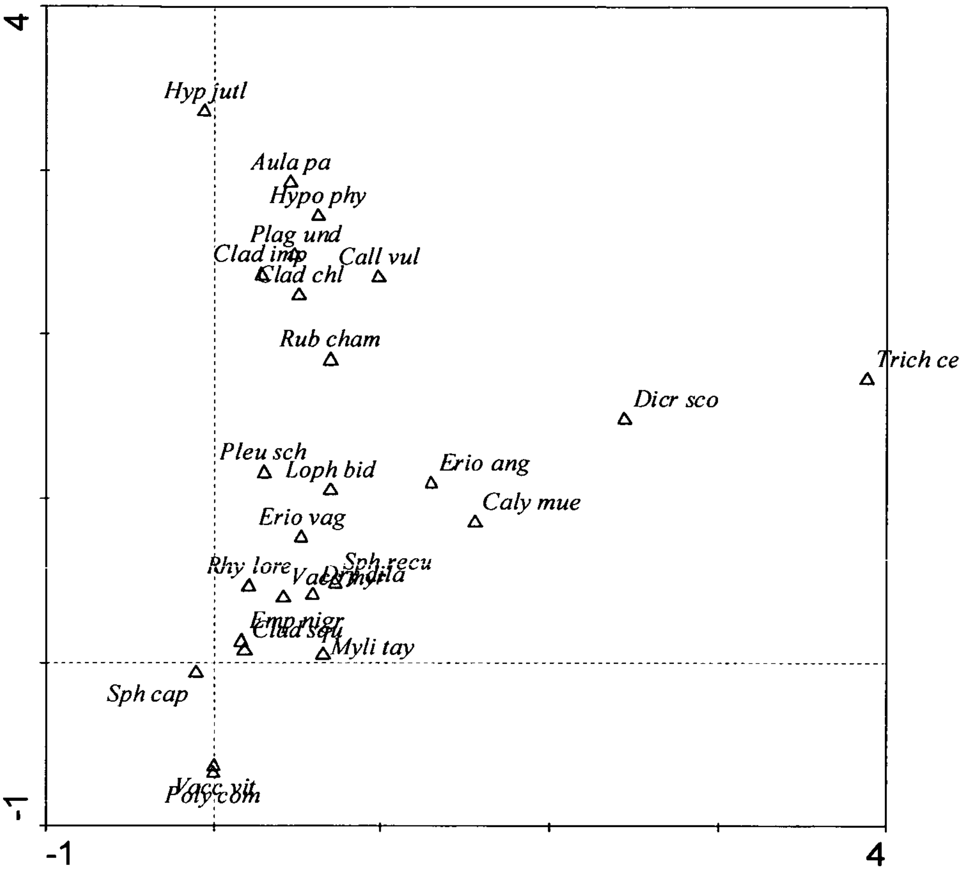

Figure 3.5: Axes 1 and 2 of a DCA of species percentage cover data showing species from Hard Hill. Plot codes are as in Table 3.3. Axes 1 and 2 accounted for 17.2 % and 10.9 % respectively of total variation in vegetation data.

Figure 3.6 shows a species ordination diagram of an RDA of the seventy two relevés from the Hard Hill data, only the fifteen most abundant species are depicted. Axes 1 and 2 accounted for 21.4 % and 5.6 % respectively of total variation in vegetation data and 77.2 % and 20% respectively of species-environment relationship. Restricted Monte Carlo permutation test according to the split plot structure of the experiment revealed the first axis to be highly significant ($p<0.002$). Forwards selection of the treatments revealed all treatments to be significant ($p<0.05$) predictors of species composition. *C. vulgaris, H. jutlandicum, C. portentosa, P. schreberii, P. undulatum* and *R. loreus* all appear to increase towards the 0 burn treatment. *P. commune, S. capillifolium, V. vitis-idaea* and *V. myrtillus* all increase towards 10 year rotational burn. *E. angustifolium* and *D. scoparium* towards 20 year burn whereas *C. muelleriana* seems to have some preference for burning treatments but intermediate in terms of 10 and 20 year burning treatments. *E. nigrum* subsp. *nigrum* and *A. palustre* appear to have predilection for ungrazed plots.

Here there is clear evidence that the abundance of species show preference for certain management treatments. This therefore substantiates the hypothesis that anthropogenic management affects the vegetation of blanket bog.

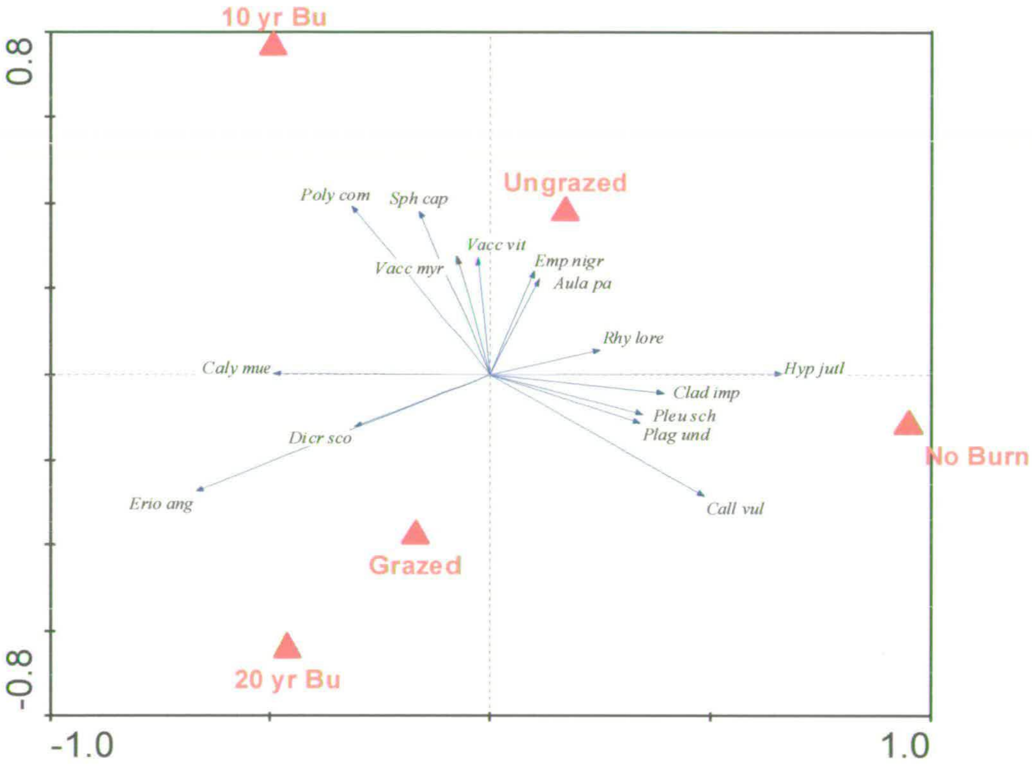

Figure 3.6: Axes 1 and 2 of an RDA of species percentage cover data against site treatment from Hard Hill Experimental grazing and burning site. Plot codes are as in Table 3.3. Treatments are coded as nominal variables: grazed and ungrazed; 0, 10 yr and 20 yr burn. Axes 1 and 2 accounted for 21.4 % and 5.6 % respectively of total variation in vegetation data and 77.2 % and 20% respectively of species-environment relationship. Restricted Monte Carlo permutations show axis 1 to be significant $p < 0.002$.

Community comparison

Table 3.4 classifies relevé data from experimental treatments to the NVC and the communities of Eddy et al., (1969) by reference to Rodwell (1991) and Czekanowski. Both 0 burn and 10 year rotational burn are classified as the sub community, M19a *Calluna vulgaris-Eriophorum vaginatum* blanket mire: *Erica tetralix* sub community. The 20 year rotational burn is classified as M20 *Eriophorum vaginatum* blanket and raised mire. However no distinction is made between grazing treatments. The Czekanowski similarity measure indicates that all treatments relevés are closer to the burnt community of Eddy et al., (1969) than of any of the other types (Typical, *Sphagnum recurvum*, or *Empetrum nigrum* communities) of their Calluneto – Eriophoretum or of the Trichophoretum or Eriophoretum.

Table 3.4: Community comparison of relevés data in particular experimental treatments with NVC and the Calluneto-Eriophoretum communities identified by Eddy et al., (1969) using the Czekanowski coefficient and Rodwell (1991). Community comparisons were aided by the use of ComKey computer software (Legg, Unpublished).

Treat.	Grazed	Ungrazed	Eddy et al., (1969)
0	M19a	M19a	burnt
10	M19a	M19a	burnt
20	M20	M20	burnt

The NVC communities with a PWS similarity greater than 50 to the Hard Hill samples and Eddy et al., (1969) tabulated samples are; M17 *Scirpus cespitosus Eriophorum vaginatum* blanket mire, M18 *Erica tetralix Sphagnum papillosum* raised and blanket mire, M19 *Calluna vulgaris-Eriophorum vaginatum* blanket mire, M20 *Eriophorum vaginatum* blanket and raised mire and H12 *Calluna vulgaris Vaccinium myrtillus* heath (Rodwell, 1991).

Table 3.5 show the percentage similarity and the number of species recorded in each community. There is not only much overlap between Hard Hill and Eddy et al., (1969) samples but also between NVC communities up to 86 percent of M20 species can be found in the M19 community.

Figure 3.7 shows the relationships between these NVC communities and samples from the Hard Hill experiment and communities from Eddy et al (1969) using the PWS (Figure 3.7, a and b) and Sørensen coefficient (Figure 3.7, c and d). Species richness and dataset type were entered as co-variables to compare the data on a species composition basis only. The correlation of NVC with axes 1 and 2 would seem to imply that some relevés give high similarity to the selected NVC and others give low similarity using both coefficients. However the results appear somewhat conflicting. Firstly the positions of samples and treatment centroids appear to be opposing since the PWS gives the Hard Hill samples closer similarity to NVC than the Eddy et al., (1969) samples whereas the Sørensen gives closer similarity to the Eddy et al., (1969) samples with NVC. Sample similarity measures to H12 and M20 communities appears to be closer with Sørensen than PWS and these are shown to be closely related in Figure 3.7 (d).

The proximity of Hard Hill centroids in both analyses suggests that there is some separation of treatments, although the PWS analysis seems to separate centroids more clearly and separation along axis 2 suggests some affinity to H12. This may highlight the greater abundance of *Calluna* in some relevés particularly associated with the 0 burn treatment. The Sørensen coefficient separates treatments along axis 1 which indicates closer affinity to M19 than the other NVC. Therefore, Hard Hill management treatments appeared to be separated more on their similarity to the M19 community but they are still close together.

Thus it would appear that blanket bog vegetation subjected to different management cannot be distinguished definitively by reference to the NVC.

Table 3.5: Percentage species match expressed as a percentage of the species found in community row with community column and number of specie in each community. Community and treatment codes areas NVC and as follows: 0 burn = Hard Hill not burnt since 1954, 10 burn = Hard Hill 10-yr rotational burn 20 burn = Hard Hill 20yr rotational burn, Type = Calluneto-Eriophoretum Typical facies, S recurv = Calluneto-Eriophoretum *Sphagnum recurv*um facies, E nig = Calluneto-Eriophoretum *Empetrum nigrum* facies, E burn = Calluneto-Eriophoretum Burnt facies, E Trich = Trichophoretum-Eriophoretum typical facies and E Erio = Eriophoretum high level facies.

Comm.	H12	M17	M18	M19	M20	0 burn	10 burn	20 burn	Type	E burn	E nig	S recur	E Trich	E Erio	No. spp.
H12	100														69
M17	43	100													79
M18	46	78	100												54
M19	46	62	54	100											84
M20	58	65	60	86	100										43
0 burn	74	74	84	84	68	100									19
10 burn	67	67	81	86	71	81	100								21
20 burn	65	70	75	80	80	75	85	100							20
Type	42	56	59	78	48	25	27	23	100						64
E burn	50	62	62	79	65	41	41	41	94	100					34
E nig	52	60	58	81	60	33	31	29	100	58	100				48
S recur	56	67	67	92	67	36	39	36	100	69	81	100			36
E Trich	47	70	79	83	51	30	30	26	79	45	58	57	100		53
E Erio	61	73	61	82	79	36	36	33	82	45	82	55	64	100	33

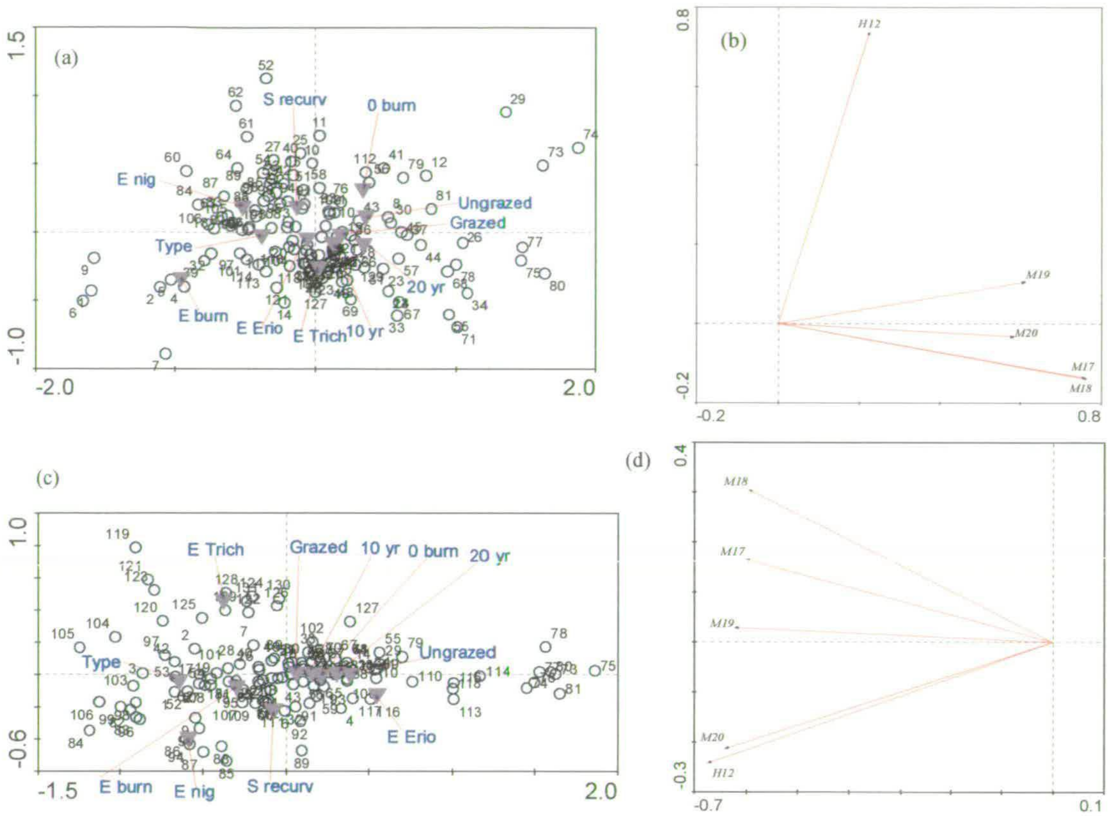

Figure 3.7: Axes 1 and 2 of PCA plots of Hard Hill samples and Eddy et al (1969) Calluneto-Eriophoretum communities and contribution of NVC communities to the PCA ordination subspace, using Presence Weighted Similarity (a) and (b) and Sørensen coefficient (c) and (d), to NVC communities M17, M18, M19, M20 and H12. Number of species in a sample and dataset type were used as co-variables to remove effect of species richness and differences in data collection. Codes for Eddy et al., (1969) data are: Calluneto-Eriophoretum *Empetrum nigrum* facies = E nig, Calluneto-Eriophoretum *Sphagnum recurvum* facies = S recurv, = Calluneto-Eriophoretum Burnt facies = E burn, Calluneto-Eriophoretum Typical facies = Type, Trichophoretum typical facies = E Trich and Eriophoretum high level facies = E Erio. Treatments and communities are plotted as centroids of samples in particular treatments or community. Axes 1 and 2 accounted for 76.3 % and 14.9 % respectively of total variation in data of PWS plots and 90.9 % and 6.3 % respectively of Sørensen plots. Community and treatment codes are as Table 3.4.

3.4.2 Forsinard

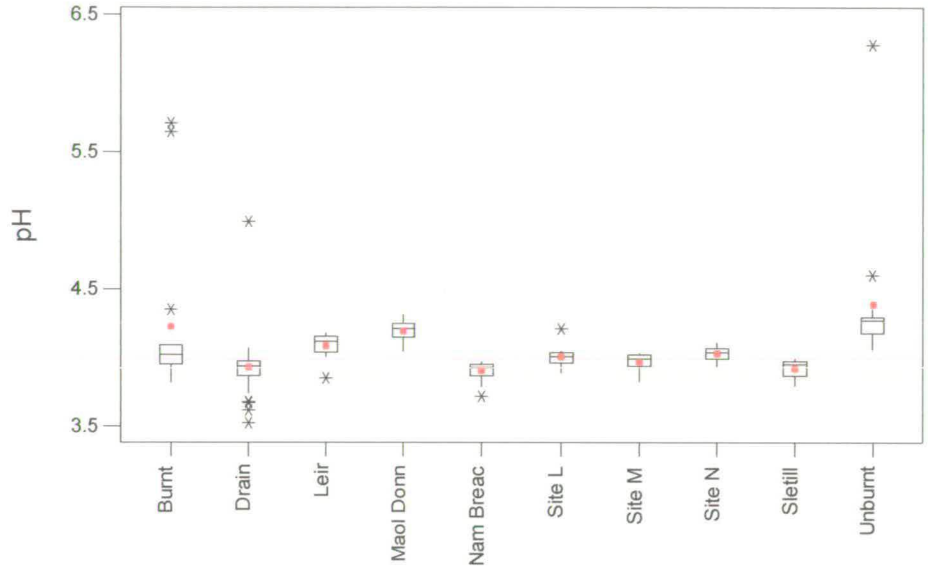

Figure 3.9: Boxplots of pH by site from the Forsinard reserve (n = 15). Red dots indicate mean and * represents outliers.

Figure 3.9 show boxplots of pH by site from the Forsinard reserve. All sites have a low mean pH, below 4.5; with Maol Donn and the two fire sites having the highest mean values. However, both the mean values for the fire sites appear to be affected by outlying points with a few samples having a relatively higher pH, it is possible these samples may have been affected by ash. The lowest mean pH appears to be associated with the Drain site, Sletill and Nam Breac.

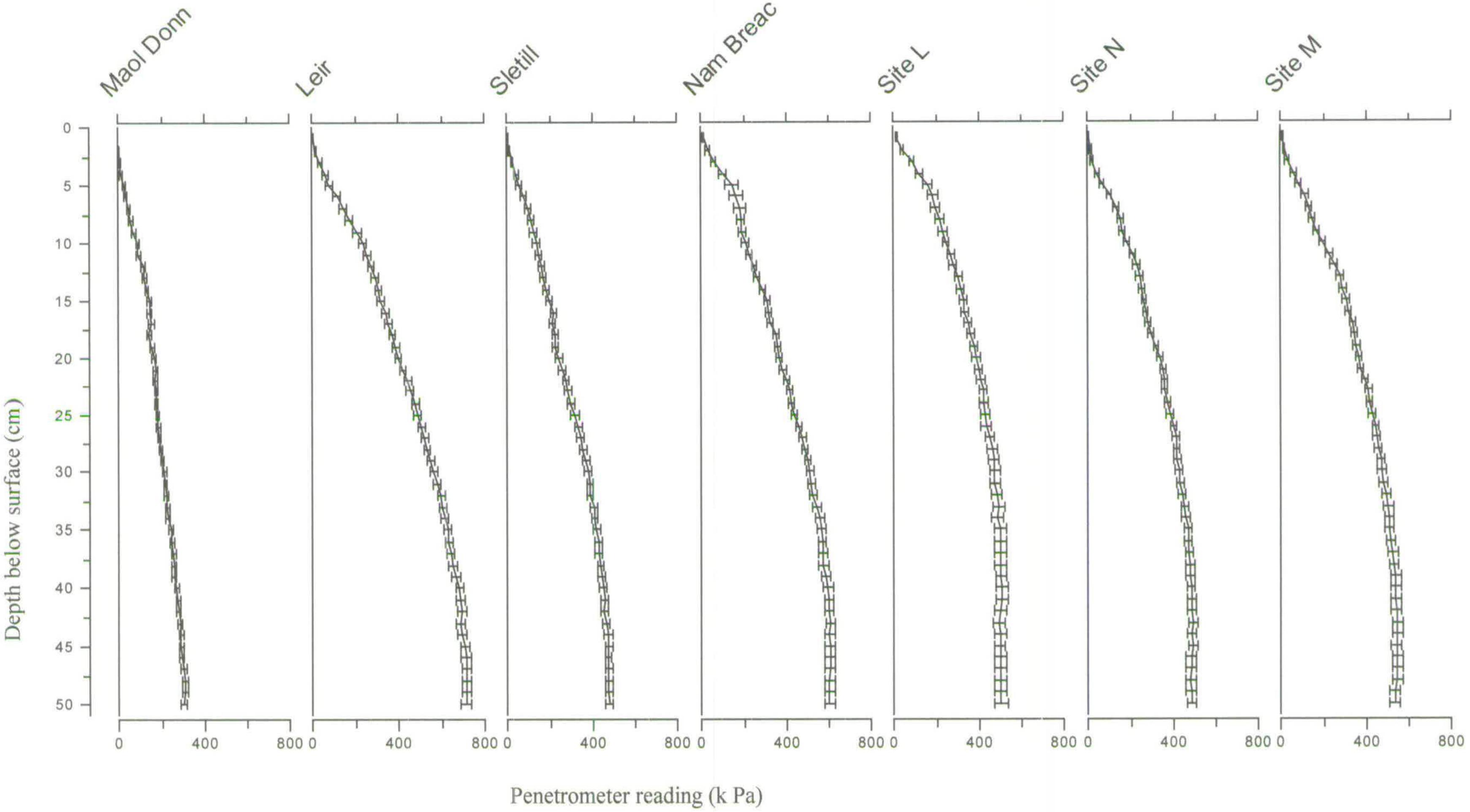

Figure 3.10: Mean (+/- SE) penetrometer readings (k Pa) every cm for 7 sites in the Forsinard reserve (n = 50).

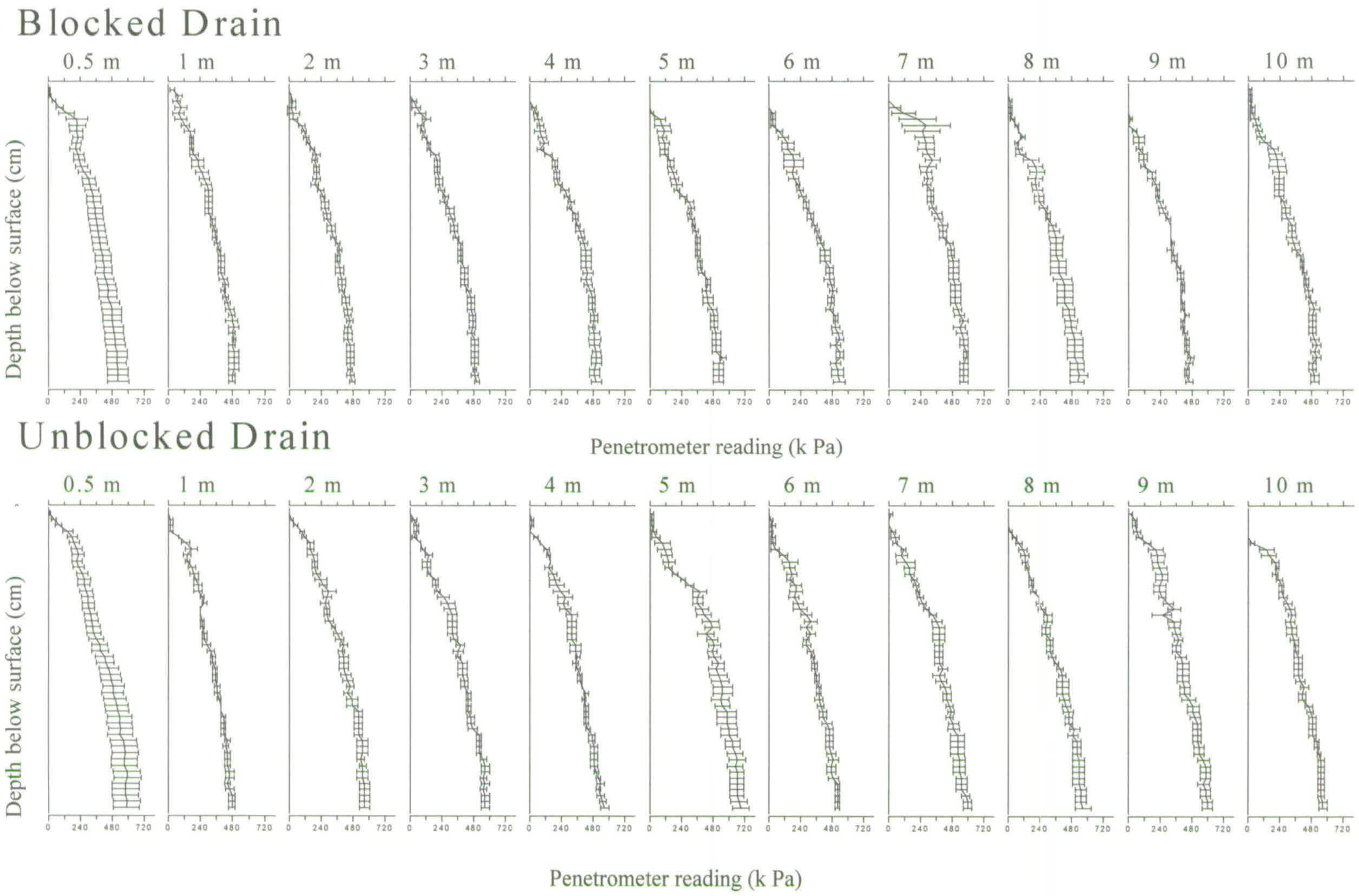

Figure 3.11: Mean (+/- SE) penetrometer readings (k Pa) per cm depth for 10, distance from drain, transects from the Cross Lochs Drain site (n = 5).

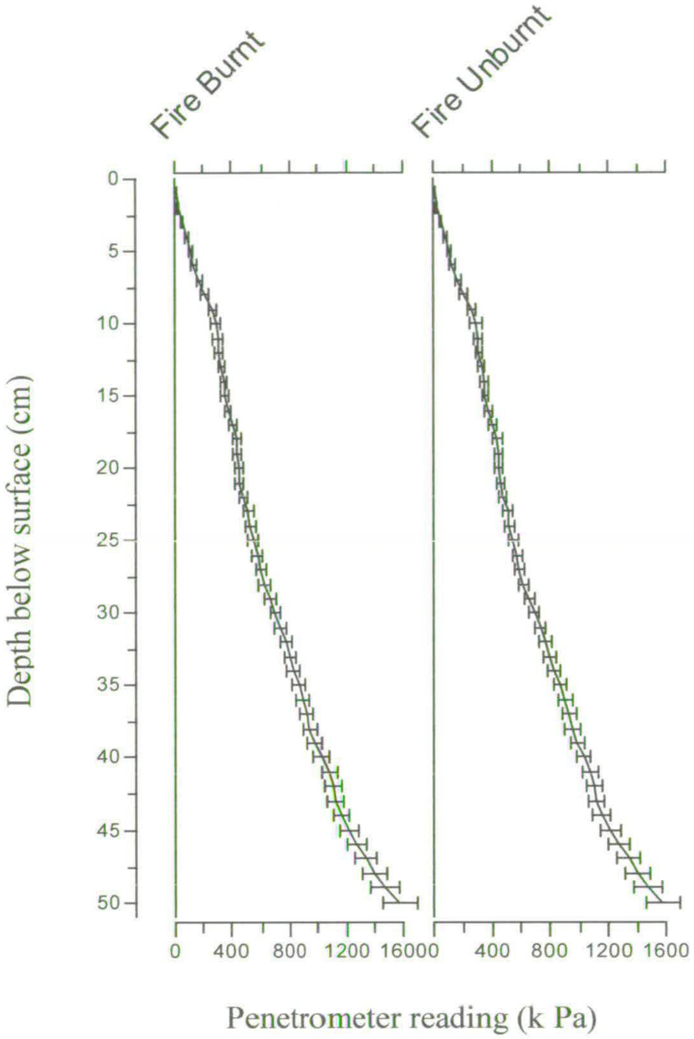

Figure 3.12: Mean (+/- SE) penetrometer readings (k Pa) every cm depth for the unburnt and burnt sites in the Forsinard reserve (n = 50).

Figure 3.10 to 3.12 show means of penetrometer readings per cm depth (+/- SE) for each of the nine sites in the Forsinard reserve. Figure 3.10 clearly shows that Maol Donn has the lowest readings of any of the sites indicating that this site has much softer peat. Leir appears to have the highest readings of these seven sites and Nam Breac and site L (and perhaps also M and N) have higher readings nearer the surface. Although there is some apparent variation in penetrometer readings, overall there appears to be little difference between the blocked and unblocked drains when comparing distance from drain (Figure 3.11) also, readings appear within the ranges of the other sites in Figure 3.10. However there may be some differences near the surface, as on balance the blocked drain readings appear to be slightly lower until about 5 cm. This may indicate some subsidence of the peat in the unblocked drain but this is subjective. There appears to be no differences between the two fire treatments but the readings do reach almost double the readings from the other sites (Figure 3.12). This may be because this site has shallower peat and may be the influence of the denser mineral soil beneath the peat; however, even readings at shallower depth are much greater than any of the other sites. Therefore, this site appears to have much denser peat.

Table 3.6 shows the number of footprints and faeces found in relevés for each of the sites sampled at Forsinard. Footprints appear to be more prevalent at Nam Breac Site M Site N and Site L and Sletill. Sheep and deer faeces were detected in the Fire Unburnt site though as this is very close to the burnt site this can be regarded as representative of both. Hare appear in Nam Breac and Leir, with evidence of grouse also at Nam Breac.

Table 3.7 shows the species recorded from the vegetation survey of the nine sites in the Forsinard reserve from a total of 185 relevés. Presence of species at particular sites and species codes for ordination diagrams are also included; species are arranges in order of abundance in terms of the number of relevés they are present in. There are a total of forty-two species (plus two others: undifferentiated algae and bare peat) that include nineteen vascular plants, fourteen mosses, four liverworts and five lichens. Of these only *Betula nana* L. is regarded as a nationally scarce species (a scarce species occurs in 16-100, 10 km^2 in the UK) and is a Local Biodiversity Action Plan (LBAP) priority species (Russell et al., 2004).

Table 3.6: The species faecal count and number of footprints found in 72 relevés for each of the sites sampled at Forsinard reserve.

	Footprints	Faecal counts			
	Red Deer	Red Deer	Sheep	Hare	Red Grouse
Site	*Cervus elaphus* L.	*C. elaphus* L.	*Ovis aries* L.	*Lepus timidus* L.	*Lagopus lagopus* L.
Nam Breac	17	-	-	16	1
Sletill	2	-	-	-	-
Leir	-	-	-	17	-
Maol Donn	-	-	-	-	-
Fire Burnt	-	-	-	-	-
Fire Unburnt	-	5	6	-	-
Site L	4	-	-	-	-
Site M	18	-	-	-	-
Site N	9	-	-	-	-
Bottom Drain	-	-	-	-	-
Middle Drain	-	-	-	-	-
Top Drain	-	-	-	-	-

Table 3.7: Species, Species code, site presence and total number of relevés for each species recorded from total of 185 relevés from Forsinard and Dorrery Nature Reserve. Species are arranged in order of abundance of the total number of relevés they are present in. P = presence.

Species	Species code	Nam Breac	Sletill	Leir	Maol Donn	Fire Burnt	Fire Unburnt	Site L	Site M	Site N	Drain Centre	Drain Unblocked	Drain Blocked	Drain pooled	No. relevés
Trichophorum cespitosum (L.) Hartm.	Tri cesp	P	P	P	P	P	P	P	P	P	P	P	P	P	309
Erica tetralix L.	Eric tet	P	P	P	P	P	P	P	P	P	P	P	P	P	307
Eriophorum angustifolium Honck.	Erio ang	P	P	P	P	P	P	P	P	P	-	P	P	P	259
Calluna vulgaris (L.) Hull	Cal vulg	P	P	P	P	-	P	P	P	P	P	P	P	P	257
Narthecium ossifragum (L.) Huds.	Nar ossi	P	P	P	P	P	P	P	P	P	P	P	P	P	220
Caldonia portentosa (Dufour) Coem.	Clad port	P	P	P	P	P	P	P	P	P	P	P	P	P	200
Bare peat	Bare peat	P	P	P	P	P	-	P	P	P	-	P	-	P	187
Sphagnum cuspidatum Ehrh. ex Hoffm.	Spha cusp	P	P	P	P	-	-	P	P	P	-	-	-	-	176
Racomitrium lanuginosum (Hedw.) Brid.	Rac lanug	P	P	P	P	-	P	P	P	P	-	P	P	P	160
Sphagnum capillifolium (Ehrh.) Hedw.	Spha capi	-	P	P	P	P	P	P	P	P	P	P	P	P	141
Myrica gale L.	Myr gale	P	-	-	-	P	P	P	-	P	P	P	P	P	116
Odontoschisma sphagnii (Dicks.) Dumort.	Odon spha	P	P	P	P	-	-	P	P	P	-	P	P	P	116
Cladonia arbuscula (Wallr.) Rabench	Clad arb	P	P	P	P	-	-	P	P	P	-	-	-	-	114
Drosera anglica Huds.	Dros ang	P	P	P	P	-	-	P	P	-	-	P	P	P	108
Sphagnum papillosum Lindb.	Spha papi	P	P	P	P	-	P	P	P	-	P	-	-	P	59
Molinea caerulea (L.) Moench.	Moli caer	-	-	-	-	P	P	-	-	-	-	-	P	P	53

Table 3.7 continued

Species	Species code	Nam Breac	Sletill	Leir	Maol Donn	Fire Burnt	Fire Unburnt	Site L	Site M	Site N	Drain Centre	Drain Unblocked	Drain Blocked	Drain pooled	No. relevés
Drosera rotundifolia L.	Dros rotun	P	P	-	P	-	P	P	P	-	P	P	-	P	49
Carex panicea L.	Car pani	P	P	P	-	-	-	P	P	P	-	-	-	-	48
Hypnum jutlandicum Holmen & E.Warncke	Hypn jutl	P	P	P	P	P	P	P	P	P	-	P	P	P	47
Pleurozium schreberii (Brid.) Mitt.	Pleu sche	-	-	-	-	P	P	-	-	-	-	-	-	-	44
Huperzia selago (L.) Bernh. ex Schrank & C. Mart.	Hup sela	P	P	-	P	-	-	P	P	-	-	-	-	-	30
Polygala serpyllifolia Hosé	Poly serp	-	-	-	-	P	P	-	-	-	-	-	-	-	28
Sphagnum magellanicum Brid.	Spha mage	-	P	-	P	-	-	-	-	-	-	-	-	-	20
Potentilla erecta (L.) Raeusch.	Pote erec	-	-	-	-	P	-	-	-	-	-	-	-	-	12
Cladonia uncialis (L.) Weber	Clad unci	-	-	-	-	-	-	-	-	-	-	P	P	P	7
Campylopus atrovirens De Not.	Camp atro	-	-	P	-	-	-	-	P	-	-	-	-	-	6
Cladonia chlorophea (Flörke ex Sommerf.) Sprengel.	Clad chlor	P	-	-	-	-	-	-	P	P	-	-	-	-	6
Betula nana L.	Betu nan	-	P	-	-	-	-	-	-	-	-	-	-	-	6
Campylopus flexuosus (Hedw.) Brid.	Campy para	-	-	-	-	-	-	P	-	-	-	-	-	-	4
Juncus squarrosus L.	Junc squa	-	-	P	-	-	-	-	-	-	-	-	-	-	4
Scleropodium purum (Hedw.) Limpr.	Pseu puru	-	-	-	-	P	-	-	-	-	-	-	-	-	4

Table 3.7 continued

Species	Species code	Nam Breac	Sletill	Leir	Maol Donn	Fire Burnt	Fire Unburnt	Site L	Site M	Site N	Drain Centre	Drain Unblocked	Drain Blocked	Drain pooled	No. relevés
Algae	Algae	-	-	-	-	-	-	-	-	-	-	P	-	P	3
Lepidozia reptans (L.) Dumort.	Lepi rept	-	-	-	P	-	-	-	-	-	-	-	-	-	2
Hypogymnia physoides (L.) Nyl.	Hypo phys	-	P	-	-	-	-	-	-	-	-	-	-	-	2
Arctostaphyllus uva-ursi (L.) Spreng.	Arct uva	-	P	-	-	-	-	-	-	-	-	-	-	-	2
Sphagnum palustre L.	Spha palu	-	-	-	P	-	-	-	-	-	-	-	-	-	2
Dactylorhiza maculata (L.) Soó	Dact macu	-	-	-	-	P	-	-	-	-	-	-	-	-	2
Melampyrum pratense L.	Mela prate	-	-	-	-	P	-	-	-	-	-	-	-	-	2
Hylocomium splendens (Hedw.) Bruch, Schimp. & W.Gümbel	Hylo splen	-	-	-	-	P	-	-	-	-	-	-	-	-	2
Rhytididelphus loreus (Hedw.) Warnst.	Rhyt lore	-	-	-	-	P	-	-	-	-	-	-	-	-	2
Eriophorum vaginatum L.	Erio vagi	-	-	-	-	-	-	-	P	-	-	-	-	-	2
Sphagnum tenellum (Brid.) Bory	Spha tene	-	-	-	-	-	-	-	-	-	-	P	P	P	2
Cladonia bellidiflora (Ach.) Schaerer	Clad bell	-	-	-	-	-	-	-	-	P	-	-	-	-	2
Diplophylum albicans (L.) Dumort.	Diplo albi	-	-	-	-	-	-	-	-	-	-	P	-	P	1

Figures 3.13 – 3.19 show species and sample ordination diagrams from the Forsinard vegetation data, no Monte Carlo permutation tests were performed on these due to uneven sample sizes and pseudoreplication.

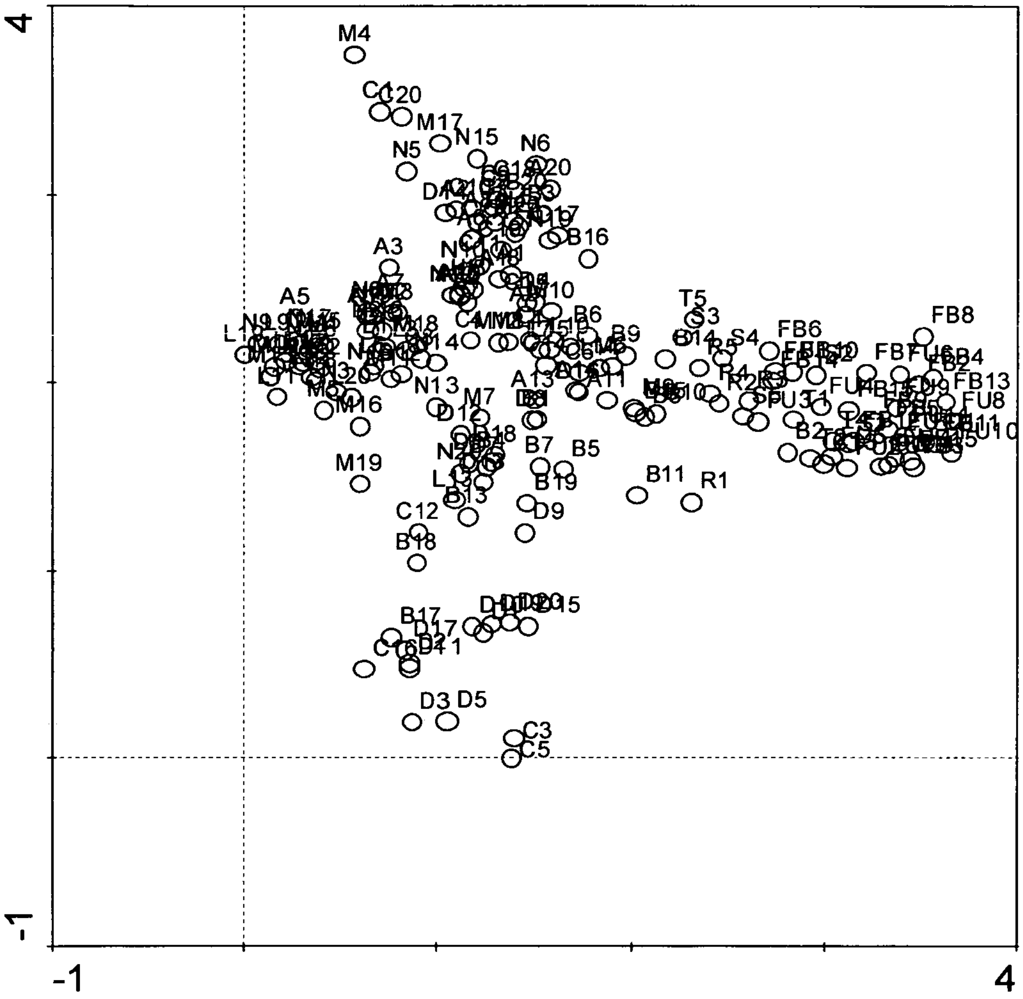

Figure 3.13: Axes 1 and 2 of DCA of samples from Forsinard vegetation relevés. Axes 1 and 2 of a DCA of species percentage cover data showing samples. Plot codes are as in Table 3.5. Axes 1 and 2 accounted for 13.1 % and 9.1 % respectively of total variation in vegetation data.

Figures 3.13 and 3.14 show axes 1 and 2 of a DCA of Forsinard species percentage cover data showing samples and species. The longest gradient length is 3.7 and axes 1 and 2 accounted for 13.1 % and 9.1 % respectively of total variation in vegetation data. Gradients of this length are generally suitable for linear or unimodal ordination methods (Lepš & Šmilauer, 2003). Samples to the right of Figure 3.13 correspond to more wet heath type vegetation with most of the Fire samples and Drain samples are found in this area of the plot. To the top left are samples containing vegetation with *Racomitrium, Cladonia* and bare peat such as found at Nam Breac and sites L, M and N. To the bottom left of the diagram are all the wetter *Sphagnum* vegetation such the Maol Donn samples, with the remaining samples in the centre. Plots used for gaseous flux measurements (Chapter 4 and 5) all encompass the variation shown in Figure 3.13 (see Appendix). Therefore, further analysis is directed towards these plots so that the relation between management vegetation and gaseous fluxes can be examined in Chapter 5.

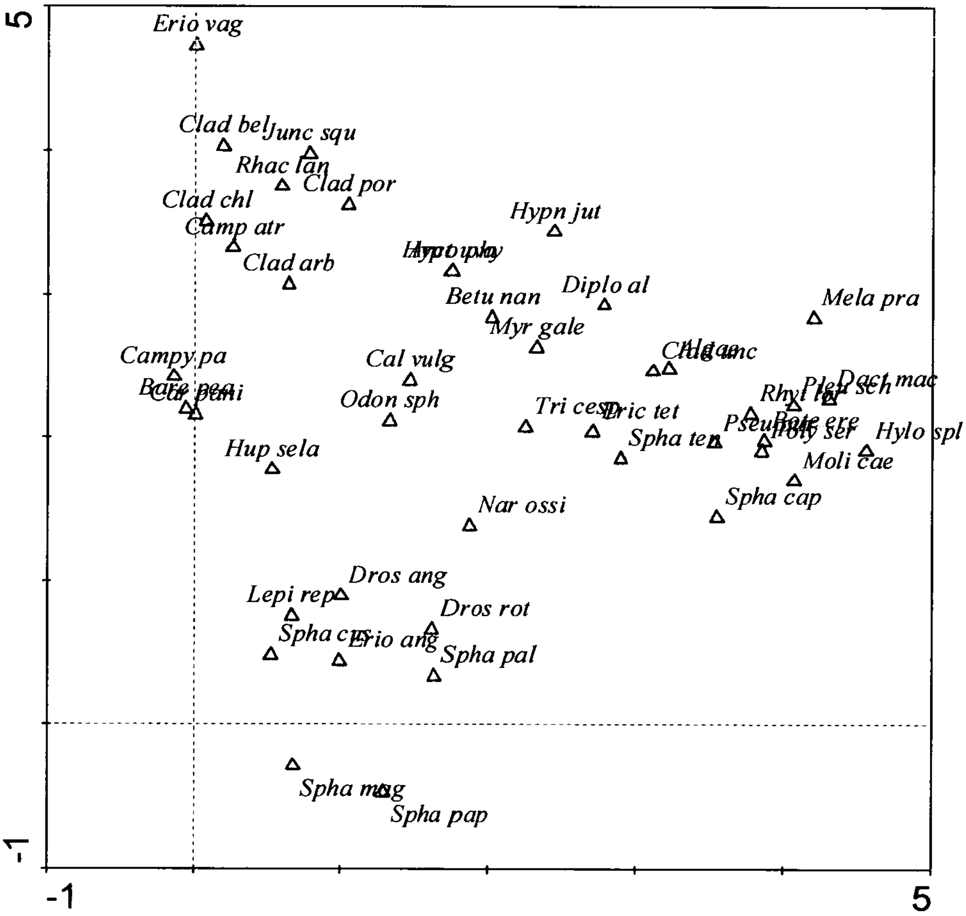

Figure 3.14: Axes 1 and 2 of DCA of species from Forsinard vegetation relevés. Axes 1 and 2 of a DCA of species percentage cover data showing samples. Species codes are as in Table 3.5. Axes 1 and 2 accounted for 13.1 % and 9.1 % respectively of total variation in vegetation data.

Figure 3.15 and 3.16 show ordination sample and species plots of a CCA of the vegetation data from only those plots where gaseous fluxes were measured with water table pH and penetrometer readings as numerical explanatory variables and site as nominal explanatory variables. Axis 1 and 2 accounted for 12.6 % and 11 % respectively of total variation in the vegetation data. Samples are strongly grouped according to the site they are sampled from suggesting that between-site variability greatly exceeds within-site variability, this is despite the sites being almost identical in term of NVC communities (Rodwell, 1991) (Table 5.1). Maol Donn appears to be separated because of its association with higher water tables and higher pH. Samples from Leir appear to be associated with higher water table but are central in terms of pH and appear to be associated with lower penetrometer readings. Leir samples also show some separation as plots C1 and C2 are correlated with higher penetrometer readings at 5 and 10 cm than C3, 4 and 5. Samples from Sletill, Nam Breac and sites L, M, and N all appear to be similar in terms of water table and penetrometer readings but separation between Sletill samples and the other samples appears to be mostly due to pH. However it should be remembered that water tables for sites L, M, and N are estimated from steel rods and may be overestimates, although they do appear to be in close agreement with Nam Breac which is a similar site in terms of general characteristics and management (Table 3.1). Samples from the drain and fire sites are strongly correlated with high penetrometer readings at 25 and 50 cm as well as low water tables. Examination of Figure 3.18 and Table 3.4 shows that some species are ubiquitous occurring in all sites e.g. *T. cespitosum* and other species being associated with particular sites and conditions *E. angustifolium*. As in the sample diagram, species abundance appears to be strongly associated with site.

Figures 3.17 and 3.18 show the within site variation where samples are analysed with between-site variation removed using site as a co-variable. Figure 3.17 indicates that within-site variation is primarily due to differences in water table and deeper penetrometer readings. Higher penetrometer readings at 5 cm and 10 cm are then associated with the remaining variation. However, there is a corresponding decrease in the length of the gradients of the axes compared to that of the between site variation shown in Figure 3.15 and the explained variation of both axes 1 and 2 is lower at 7.1 % and 2.9 % respectively.

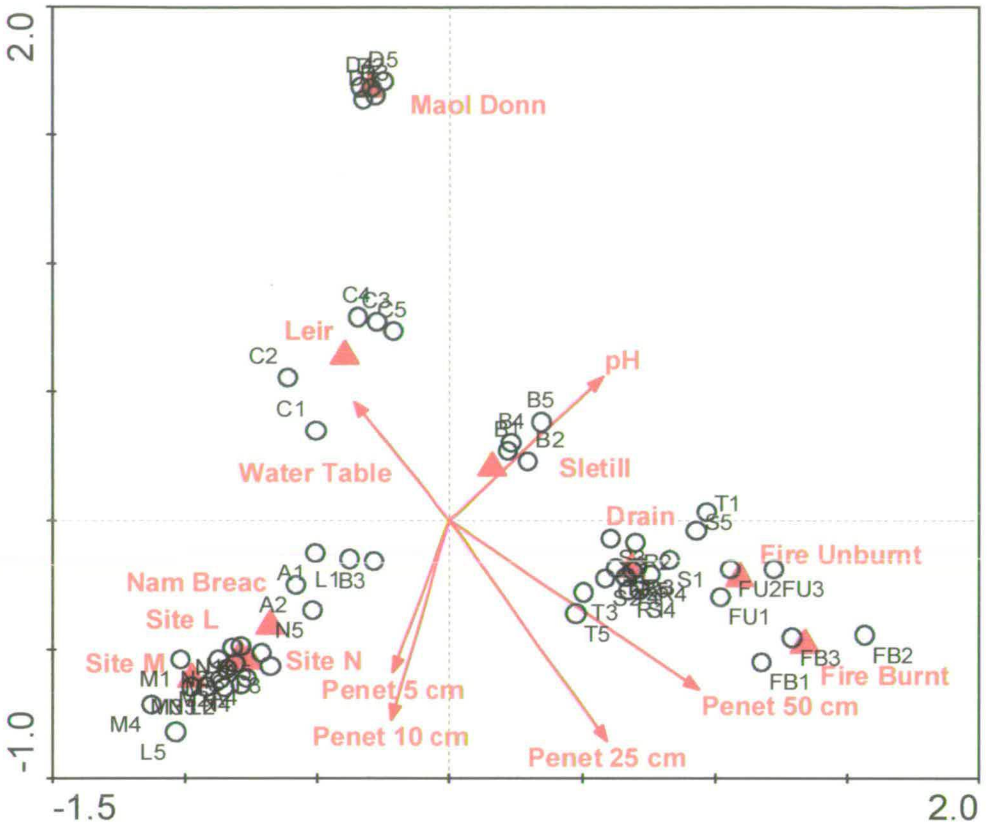

Figure 3.15: Axes 1 and 2 of CCA sample plot, of species percentage cover data from plots used for gaseous flux measurements in nine peatland sites on the RSPB Forsinard Reserve. Plot codes are as in Table 3.4. Explanatory variables used are: mean peat penetrometer data at 5, 10, 25 and 50 cm (n, 50), mean site pH (n, 50), mean July water table, and site coded as dummy variables. Axes 1 and 2 accounted for 12.6 % and 11 % respectively of total variation in vegetation data.

Figure 3.16: Axes 1 and 2 CCA species plot, of species percentage cover data from plots used for gaseous flux measurements in nine peatland sites on the RSPB Forsinard Reserve. Species codes are as in Table 5.4. Explanatory variables used are: mean peat penetrometer data at 5, 10, 25 and 50 cm (n, 50), mean site pH (n, 50), mean July water table, and site coded as dummy variables. Axes 1 and 2 accounted for 12.6 % and 11 % respectively of total variation in vegetation data.

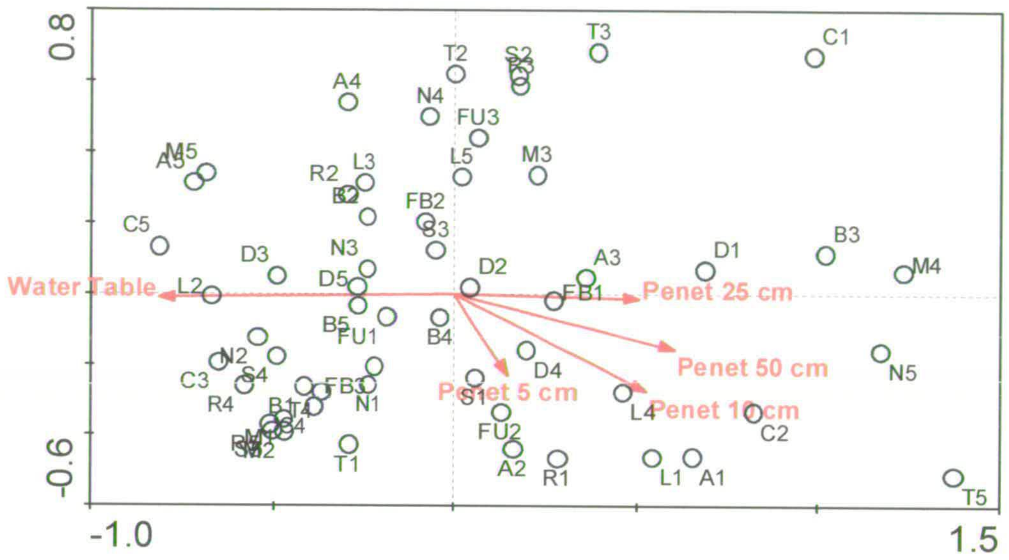

Figure 3.17: Axes 1 and 2 of CCA sample plot, of species percentage cover data from plots used for gaseous flux measurements in nine peatland sites on the RSPB Forsinard Reserve. Plot codes are as in Table 5.2. Explanatory variables used are: mean peat penetrometer data at 5, 10, 25 and 50 cm mean July water table, and site coded as co-variable. Axes 1 and 2 account for 7.1 % and 2.9 % respectively, of total variation in vegetation data.

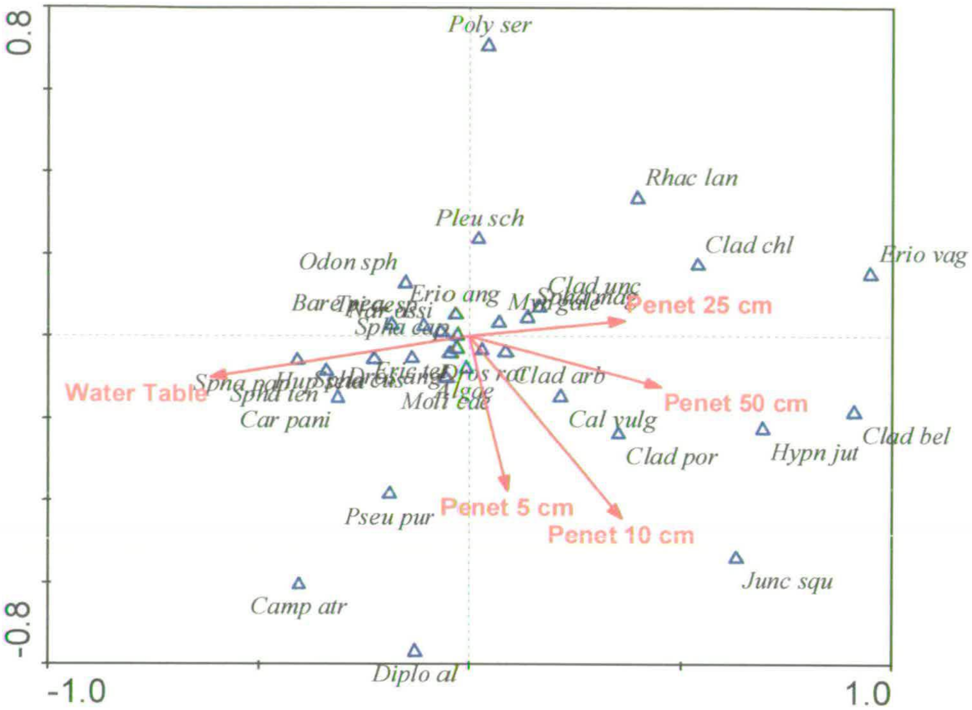

Figure 3.18: Axes 1 and 2 of CCA species plot, of species percentage cover data from plots used for gaseous flux measurements in nine peatland sites on the RSPB Forsinard Reserve. Species codes are as in Table 5.4. Explanatory variables used are: mean peat penetrometer data at 5, 10, 25 and 50 cm mean July water table, and site coded as co-variable. Axes 1 and 2 account for 7.1 % and 2.9 % respectively, of total variation in vegetation data.

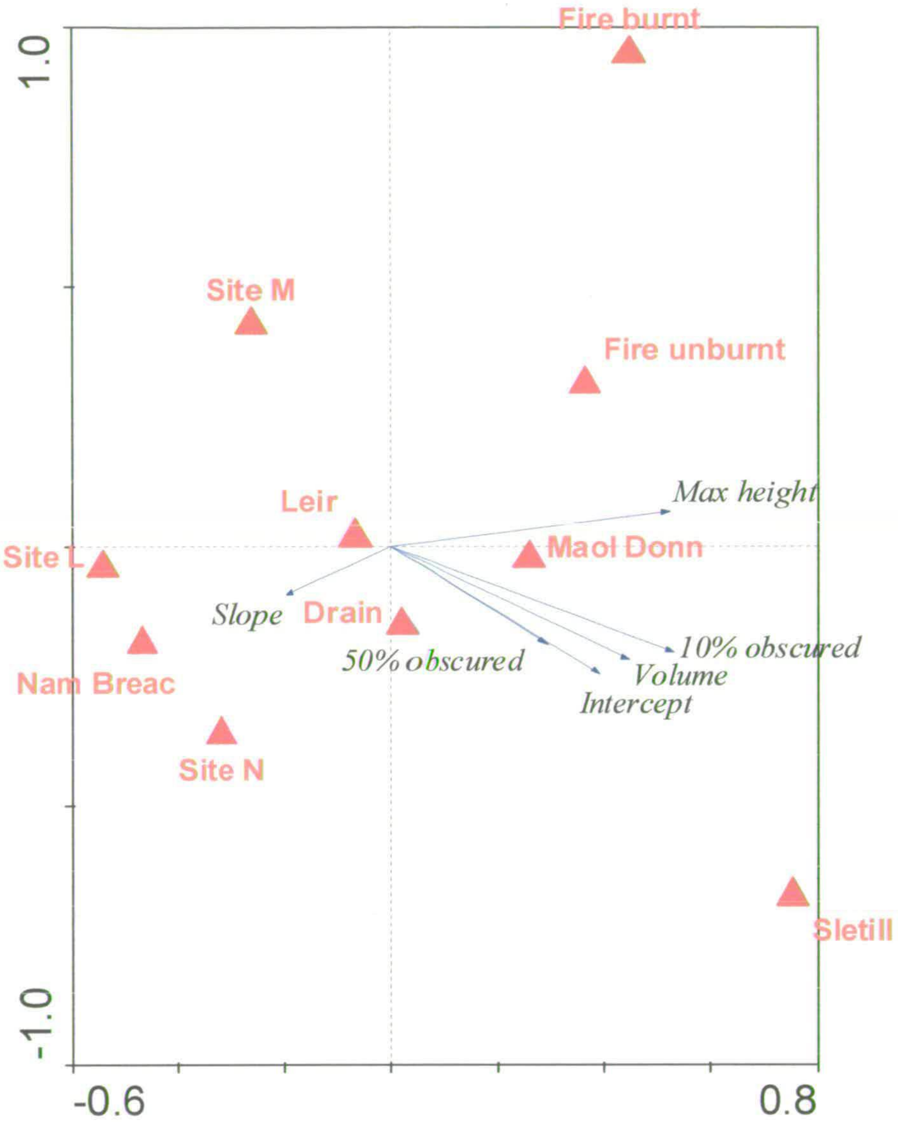

Figure 3.19: Axes 1 and 2 of RDA of PObscured data for vegetation plots with sites as nominal explanatory variables.

Figure 3.19 shows an RDA of the PObscured data with sites as explanatory variables. This shows clear differences in site vegetation structure with Sletill having the largest values of all variables except slope. Nam Breac and site L and N seem to be similar in structure with low vegetation but high slope (open sparse canopy). Differences between the two fire sites seem to be in terms of slope and maximum height. The burnt site seems to show higher vegetation this is because one of the first species to come through after the fire was *Molinea caerulea*, which forms a high canopy. Also, the burnt site has a more negative slope indicating a relatively denser canopy than the unburnt site this may be indicating a faster growth response than the unburnt site due to available nutrients, but in the absence of information on nutrient availability this is speculative. Site M appears to have the lowest values associated with the PObscured data because this site is characterised by large areas of bare peat.

3.5 Discussion

3.5.1 Management effects on vegetation, experimental evidence

From the evidence presented above it is clear that burning and grazing have had direct effects on the vegetation of the Hard Hill plots. The evidence by other authors was reviewed by Adamson and Kahl (2003) and is in agreement with the findings here (Rawes & Williams, 1973; Rawes & Hobbs, 1979; Hobbs & Gimingham, 1980; Hobbs, 1981; Hobbs, 1984). Briefly from Adamson and Kahl (2003), the evidence has lead to suggestions that a 20 year burning rotation on blanket bog is better since it allows *Calluna* enough time to regenerate. However, at Moor House *Calluna* is thought to reach a "steady state" in the absence of fire, in which shoot layering allows the *Calluna* to keep pace with the growth of *Sphagnum* (Forrest, 1971). This may indicate that fire makes a questionable management tool at this site even for grouse (Adamson & Kahl, 2003). However, the evidence presented above shows that here it is not only *Calluna* that has been shown to have preference for certain burning rotations. Removal of burning and grazing was shown to increase the growth of *Rubus chamaemorus* on the Hard Hill site (Taylor & Marks, 1971; Marks & Taylor, 1972). Although *R. chamaemorus* is neither the most prominent species nor a great contributor to peat growth nonetheless, the implication of this and the evidence presented in this study are that certain species are encouraged or discouraged according to the particular management. Since different species have different photosynthetic rates there is potential here for an impact upon ecosystem carbon dynamics. The value of the Hard Hill site as a long-term experiment is indisputable, however, the results may not be indicative of blanket bog in the UK, as Moor House is one site and may be anomalous. Moor House is an NNR, designated because it represents one of the best examples of habitat type in England and is managed for conservation, the majority of blanket bog in the UK is unlikely to be of similar 'quality' to Moor House and is managed for specific economic goals such as animal production or sporting activities.

Community comparison

There are two interesting points to be made from the NVC community comparison. Firstly, the inability to assign different management treatments to distinct NVC communities, suggests that the mire NVC may be insensitive to difference in management (at least at the Hard Hill site) even when clear statistical evidence of treatment effects on species composition is present. This may be partly because of the large overlap in species i.e. the mire communities analysed here have many species in common.

In Figure 3.7, the Eddy et al., (1969) centroids and samples in the Sørensen analysis have higher similarity to NVC but in the PWS analysis the Hard Hill samples appear to have a higher similarity to NVC. This may be partly because of the different way the similarity coefficients are calculated. Sørensen similarity (and Czekanowski) includes the number of species in the community as well as in the sample thus species that do not appear in NVC but do appear in samples and vice versa are included in the calculation. NVC communities are an abstract and include species from samples from all around UK and a perfect match would be incongruous. It would seem then that Sorensen (and Czekanowski) calculations include much redundancy and including these species is probably unnecessary. This may also have affected the ordination by translating to the position in the ordination being based more preferentially on species that are not really part of the typical NVC types. Attempting to remove some of this by including species richness and dataset type has removed some variability but not all. PWS on the other hand calculates similarity from matching species in the sample and community thereby reducing this redundancy and making the similarity more interpretable in terms of the sampled community relationship to NVC.

It would seem that NVC has little to offer in terms of differentiating site management in these mire communities and that one must be careful in the choice of similarity index. Ecological contractors commonly use the Czekanowski coefficient to determine NVC but this like Sørensen may be misleading by including redundancy in the similarity calculation. There is therefore, a large degree of subjectivity in assigning communities.

3.5.2 Management effects on vegetation evidence from Forsinard

Although all sites have a low pH and can be classified as ombrotrophic (Wheeler & Proctor, 2000) there may be differences in nutrient availability not detected by pH. At Maol Donn site characteristics may be slightly different than at any of the other sites. Maol Donn is located in what may once have been a basin certainly the surrounding ground to the north, the east and west, slopes towards this site. It is possible that there is some groundwater influence and a small burn drains to the west of the sampled plots. If this is the case this may be exacerbated by proximity to the forest track influencing nutrients from run off. The higher pH found at the unburnt site and the prevalence of outlying points at both fire sites indicate that these sites are more variable than the other sites and it is probable that samples are influenced by the presence of ash.

Peat compression as indicated by the penetrometer readings also shows differences among sites. Again Maol Donn stands out as a site much softer peat at the other sites. At the other extreme the fire sites are located on peat that is much more compressed. This may be the influence of shallower peat but it may also be indicative of management practice. Fire appears to be common to the vicinity (just outside the Forsinard reserve) probably used to encourage the 'early bite' for deer and sheep rather than management for red grouse. It may be possible then that through the use of fire animal utilisation of these sites may be increased and hence fire may lead indirectly to more compressed peat. The slightly higher readings nearer the surface at Nam Breac, sites L, M and N may also be due to animal trampling, it is certain that deer footprints were more prevalent at these sites (Table 3.4).

The ordination of vegetation samples from Forsinard, appear not only to provide evidence differences in vegetation but also in structure. This site association of these differences are considered to be synonymous with management. This would appear to offer further support to the experimental evidence of Hard Hill. Management effects on the vegetation, structure and peat characteristics may affect the carbon fluxes in several ways. Changes in vegetation will undoubtedly affect photosynthesis through differences in species composition. Similarly effects on vegetation structure will affect the photosynthetic rate through alterations in biomass. Differences in peat compression may affect the ability of gasses to transport though peat and affect thermal properties of the peat, which will have implications on the processes of respiration, methanogenesis and methanotrophy.

The question remains though how representative these sites are, in terms of vegetation and management.

The Scottish blanket bog inventory lists the most common NVC community types to Scotland as M17 and M19 and mosaics containing these communities (Quarmby et al., 1999; Johnson & Morris, 2000c, a, b, d, 2001). The community identified for Hard Hill was M19 so it may be that the vegetation composition may be somewhat indicative of blanket bog in the UK. In terms of vegetation the most common NVC community to the Caithness, Sutherland and Orkney region are mosaics of M17 *Scirpus cespitosus-Eriophorum vaginatum* mire, M15 *Scirpus cespitosus-Erica tetralix* wet heath and M19 *Calluna vulgaris-Eriophorum vaginatum* blanket mire (Johnson & Morris, 2001). The sites sampled in Forsinard cover both the M17 and M15 communities. Of the approximately 10 NVC communities that could be said to cover ombrotrophic bog the most common to Scotland are M17 and M19 and mosaics containing these communities (Quarmby et al., 1999; Johnson & Morris, 2000c, a, b, d, 2001). Therefore the sites may be somewhat representative in terms of general vegetation composition, in the widest sense.

As indicated in Chapter 1, there is little information on the geographical spread of blanket bog management making it difficult to gauge how representative the Forsinard or the Hard Hill sites are to the general management of UK peatlands. As the NVC does not differentiate the Hard Hill treatments or the Forsinard sites, the NVC classifications also offer little in gauging how representative these sites are in terms of management. Given the uncertainties of the geographical spread of blanket bog management, the insensitivity of the NVC to differences in management is unfortunate since it may have allowed indications of management on a wider scale. Evidence of management effects through NVC have been detected elsewhere. In Northern England NVC communities were related to particular experimental treatments in a grassland fertiliser grazing and mowing study (Smith et al., 1996; Smith et al., 2000). Similarly in the park grass experiment at Rothamstead NVC communities could be related to treatment effects (Dodd et al., 1994). Examination of mire NVC communities in Suffolk were found to change over the period 1959 to 1991, and this could be related to changes in traditional management practices (Fojt & Harding, 1995). The insensitivity found here may be because the management does not affect species composition sufficiently to allow differences to be detected. However, that statistical differences in vegetation composition were detected would appear to offer no support for this. Further there is undoubtedly a degree of subjectivity with which NVC communities are classified this then would also make NVC a less attractive indicator of management practice.

3.6 Conclusions

- Experimental evidence from the Moor House Hard Hill experiment showed that vegetation composition is determined by the management practices of burning and grazing.
- Survey evidence from Forsinard determined difference between sites in terms of pH, peat compaction, animal utilisation, vegetation composition and vegetation structure
- There are therefore differences in vegetation and structure, which in this study are considered to be associated with site and therefore management at Forsinard.
- However, that both Moor House and Forsinard are site-specific studies means that more research is required for the applicability of these studies to the UK situation.
- The NVC method is not indicative of site management at either Hard Hill of Forsinard.

- The development of further methodology to assess the geographical spread and intensity of management of blanket bog in the UK is desireable.

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Chapter 4: Environmental relationships to the gaseous carbon fluxes of blanket bog

4.1 Introduction

That biological processes such as photosynthesis, respiration and methanogenesis are influenced by climate variables is well established. Light, often measured as photosynthetically active radiation (PAR) and air temperature, are important drivers for net exchange of carbon dioxide (CO_2) during daylight (Mooney & Ehleringer, 1997; Grace, 1999). To a lesser extent relative humidity (RH) may have an effect on net exchange of CO_2 through influences on the stomata (Pospíšilva & Šailurcek, 1997; Grace, 1999; Long, 1999). Net exchange of CO_2 in the dark and net CH_4 fluxes are strongly related to temperature (Davidson & Schimel, 1995; Farrar, 1999; Joabsson et al., 1999; Long, 1999; Basiliko et al., 2003) indicating enzymatic processes and also water table can be related to fluxes of methane (CH_4) (Davidson & Schimel, 1995; Joabsson et al., 1999; Basiliko et al., 2003). That these relationships hold for peatland sites and species in the laboratory and in the field has also been demonstrated (Grace & Woolhouse, 1970; Dise, 1993; Roulet et al., 1993; Bubier et al., 1995; Christensen et al., 1996; Silvola et al., 1996; Waddington et al., 1996; Alm et al., 1997; Bergman et al., 1998; Hargreaves & Fowler, 1998; MacDonald et al., 1998; Bergman et al., 1999b; Kettunen et al., 1999; Christensen et al., 2000; Vourlitis et al., 2000; Aurela et al., 2001; Updegraff et al., 2001; Arneth et al., 2002; Bubier et al., 2003; Beckmann et al., 2004). Examination of these relationships has led to the use of different models to examine relationships and derive supposedly meaningful biological parameters. For example, linear and exponential models have been used to describe the relationships for temperature and soil respiration (Fang & Moncrieff, 2001) and exponential, rectangular and non-rectangular hyperbola have been used to describe the relationship between light and CO_2 flux (Thornley, 1976; Iqbal et al., 1997)

When resulting data appear to depart from these sound theoretical relationships, then a re-examination of experimental methods, techniques and analysis is necessary.

4.2 Study Aims

Here net carbon dioxide and methane exchange from peatlands in the North of Scotland are related to climate variables to investigate whether such theoretical relationships exist and examine any instances where observations depart from theory. Relationships will be used to derive models for use in carbon balance modelling (Chapter 5).

The following climate variables were hypothesised as important to net CO_2 exchange in the light (CO_2 light), net CO_2 exchange in the dark (CO_2 dark) and net CH_4 exchange (CH_4):

- CO_2 light: photosynthetic active radiation, air temperature and relative humidity.
- CO_2 dark: soil temperature.
- CH_4: soil temperature and water table.

4.3 Methods

4.3.1 Site Description

Details of site descriptions can be found in Chapter 3. Only sites with sufficient data were analysed here, therefore the sites used are: Nam Breac, Sletill, Leir, Maol Donn and the Cross Lochs Drain site.

4.3.2 Gas Flux Measurements

Table 4.1 details the number of plots, plot codes and sampling dates for the gas flux measurements. This approach enabled 'targeting' of measurements to small specific areas and some degree of replication. CO_2 and CH_4 flux measurements were made in the field using a static chamber (Figure 4.1). Chambers were constructed of a stainless and mild steel base frame, which was inserted roughly 10 cm into the peat. During measurements, one base frame was placed in a central plot and remained in place throughout measuring whilst another was moved from one plot to the next, leaving approximately 35 minutes between frame insertion and measurement. A polypropylene top was clamped to the base with rubber seal (draught excluder) between the chamber top and base to provide an air tight seal. Two chamber top designs, a light and dark chamber, were used for estimation of (i) net carbon dioxide exchange in the light (CO_2 light) (ii) net carbon dioxide exchange in the dark (CO_2 dark) and (iii) net methane exchange (CH_4). The light chamber sides and top were made of Propafilm-C©; this material has a high transmittance to both light and thermal radiation (Hunt, 2003). The thermal transmittance avoids warming inside the chamber allowing for measurements to be made in similar conditions to ambient. A 5-volt fan was located inside the chamber ensuring sufficient mixing of chamber air. The basal area of the chamber was 0.32 m^2 and internal volume 0.09 m^3. Chambers were placed in five random locations within a reasonably homogeneous area of vegetation at each site to be measured. One chamber location was chosen randomly as the main location and repeated measurements were made at this plot alternating with satellite locations in turn giving the chamber measurement sequence 1, 2, 1, 3, 1, 4, 5, 1. On the drainage sites at the Cross Lochs two plots are placed adjacent to an unblocked and two plots adjacent to a blocked drain with one plot located half way between the two drains. This central plot is used as the repeated plot. This configuration was repeated at three locations on the two drains: top, middle and bottom. On the fire site three plots were randomly located in each of the burned and unburned locations and measurements taken during the same day alternating between morning and afternoon at subsequent visits.

For estimating CO_2 fluxes, light and dark measurements were recorded over a five-minute period or until concentrations changed by 50 ppm from ambient. Chamber air was pumped through a drying agent (self indicating Drierite, 97% $CaSO_4$, 3% $CoCl_2$) and then into an infrared gas analyser (IRGA) (Gascard II Edinburgh Instruments) at the rate of 0.009 m^3 min^{-1}. The concentration of CO_2 was recorded every 30 seconds and flux rates were then calculated as rate of change per unit time. Chamber air temperature (°C), and relative humidity (%) were logged using a Hobo Pro Series H8 logger, Onset Computer Corporation, and photosynthetically active radiation (PAR $\mu mol\ m^{-2}\ s^{-1}$) was logged using a Datahog PAR logger, Skye Instruments Ltd. Soil temperature at 10 cm using a CheckTemp Probe thermometer. Water table was routinely measured using dip wells inserted 50 cm into the peat, constructed from 2 cm diameter plastic tubes with 5 mm holes drilled at regular intervals into the sides to allow passage of water (Brooks & Stoneman, 1997). Water table for sites L, M and N was estimated from steel rod corrosion (Bridgham et al., 1991); this appeared to overestimate the mean depth of the water table when compared with measurements at two dip wells.

Methane measurements were made using the dark chamber but over a 30 minute period with a gas collection made every 10 minutes including one at time zero. Chamber air was collected into evacuated 20 cm^3 glass vials and stored for analysis by either a Hewlett Packard 5890 Series II or an Agilent 6890N flame ionisation gas chromatograph at The University of Edinburgh, School of GeoSciences. Vials were over-pressurised with 20 cm^3 of chamber air to allow detection of leaks.

Table 4.1: Number of plots, plot codes and dates of gas flux and vegetation sampling from Forsinard sites 2003-2005.

Site	No. gas flux plots, plot codes	Gas flux sampling dates
Nam Breac	5, A1-A5	14 Nov 03, 17 Dec 03, 12 Mar 04, 10 Apr 04, 11 July 04, 19 Aug 04, 26 Sept 04, 11 Oct 04, 17 June 05, 26 July 05, 26 Aug 05, 26 Sept 05, 15 Oct 05
Sletill	5, B1-B5	11 Nov 03, 15 Dec 03 24 Feb 04, 9 Mar 04, 7 Apr 04, 8 July 04, 17 Aug 04, 23 Sept 04, 8 Oct 04, 19 June 05, 24 July 05, 26 Sept 05, 16 Oct 05
Leir	5, C1-C5	12 Nov 03, 18 Dec 03 11 Mar 04, 9 Apr 04, 10 July 04, 19 Aug 04, 25 Sept 04, 10 Oct 04, 18 June 05, 23 July 05, 25 Aug 05, 28 Sept 05, 21 Oct 05
Maol Donn	5, D1-D5	13 Nov 03, 16 Dec 03, 10 Mar 04, 8 Apr 04, 12 May 04, 9 July 04 18 Aug 04, 24 Sept 04, 9 Oct 04, 20 June 05, 25 July 05, 23 Aug 05, 27 Sept 05, 20 Oct 05
Fire	3 burnt FB1-FB3 3 unburnt FU1-FU3	29 July 04, 20 Aug 04, 27 Sept 04, 12 Oct 04
Site L	5, L1-L5	12 July 04
Site M	5, M1-M5	15 Aug 04
Site N	5, N1-N5	16 Aug 05
Cross Lochs Drains	6 blocked, R4, R5, S4, S5, T4, T5 6 unblocked, R2, R3, S2, S3, T2, T3 3 Centre, R1, S1, T1	21, 22, 23 June 05 27, 28, 29 July 05 27, 28, 29 Aug 05 23, 24, 25 Sept 05 17, 18, 19 Oct 05

Figure 4.1: Light (left) and dark (right) chambers used for the measurement of CO_2 and CH_4 fluxes from blanket bog at Forsinard 2003-2005.

4.3.3 Statistical Analysis

Missing Data

Climate variables (PAR, air temperature and relative humidity) between June 2004 and October 2004 were lost due to computer failure. Modelled climate data to replace missing values (see Chapter 5) were **not** included in this analysis.

The relationships between site gaseous fluxes and climate variables were explored using regression techniques. A stepwise linear regression approach was adopted to identify the strongest predictors of CO_2 flux in the light and CH_4 flux and then a combination of models was used to explore these predictors.

For CO_2 flux in light conditions a $\log_{10}$ linear response and a non-rectangular hyperbola (Thornley, 1976) were used for modelling the response to PAR. The data for CO_2 flux in light data includes the portion due to respiration i.e. it represent net ecosystem exchange rather than just photosynthetic flux. The non-rectangular hyperbola equation is more usually used as a mechanistic model of photosynthesis at the leaf level. There are theoretical grounds for wanting to separate the photosynthesis and respiration processes. However, when doing so the R^2 decreased. Had the R^2 increased then this would have provided good practical reasons for separating the two processes. However, the absence of any improvement in R2 provides a justification for electing to adopt an empirical approach from here on.

The non-rectangular hyperbola relating the flux of CO_2 and PAR can be expressed as:

$$F = \frac{(\varepsilon * Q_p + A_{max} - \sqrt{[(\varepsilon * Q_p + A_{max})^2 - 4 * \theta * \varepsilon * Q_p * A_{max})]}}{-2 * \theta} + R_d$$

Where:

F = rate of CO_2 flux,

ε = quantum yield,

Q_p = PAR,

A_{max} = maximum assimilation rate,

θ = smoothness of the curve

and R_d = dark respiration.

The non-rectangular hyperbola was fitted using the solver function in Microsoft Excel 2000 by minimising the root mean square error and maximising R^2.

For CO_2 in the dark and CH_4 flux both linear and exponential functions were used to explore flux response. The regression equations of site responses to climate variables identified by these analyses are then used to model site carbon balances in Chapter 5. Linear analyses were performed using Minitab 13, exponential functions were fitted using SigmaPlot, 9.0 and all other summary statistics and graphical plots were generated using Microsoft Excel 2000 software.

4.4 Results

Table 4.2: Results of stepwise regression of net CO_2 light flux (μmol CO_2 m^{-2} s^{-1}) and CH_4 flux (μmol CH_4 m^{-2} s^{-1}) and climate variables from selected sites located in the Forsinard Reserve. Alpha to enter and remove in model = 0.15. R^2 adjusted values are for 1st term and 1st and 2nd term together where applicable. Abbreviations are: photosynthetically active radiation (PAR, μmol m^{-2} s^{-1}), air temperature (AT, °C), relative humidity (RH, %), soil temperature (ST, °C) and water table (WT, cm below surface).

Site	Flux type	Significant model variables	R^2 adj %	p value
Nam Breac	CO_2 light	PAR	28.2	<0.001
	CH_4	ST	17.9	<0.001
Sletill	CO_2 light	PAR	37.1	<0.001
		AT	40.4	0.031
	CH_4	ST	55.1	<0.001
Leir	CO_2 light	PAR	21.2	<0.001
		RH	22.9	0.127
	CH_4	ST	16.1	<0.001
		WT	18.8	0.038
Maol Donn	CO_2 light	PAR	41.7	<0.001
		AT	43.8	0.050
	CH_4	ST	55.1	<0.001
Drain	CO_2 light	PAR	63.2	<0.001
	CH_4	None detected	-	-

Table 4.2 details the results of the stepwise analysis for the Forsinard sites. In all sites PAR was detected as the first term for CO_2 light. In both Sletill and Maol Donn air temperature, and in Leir relative humidity, added to the models but the additional improvement in R^2 adjusted values is quite low at 3.3 %, 2.1 % and 1.7% respectively. This suggests that these variables do not improve the models greatly. Subsequently only single term models are considered further and used in Chapter 5 for carbon balance modelling.

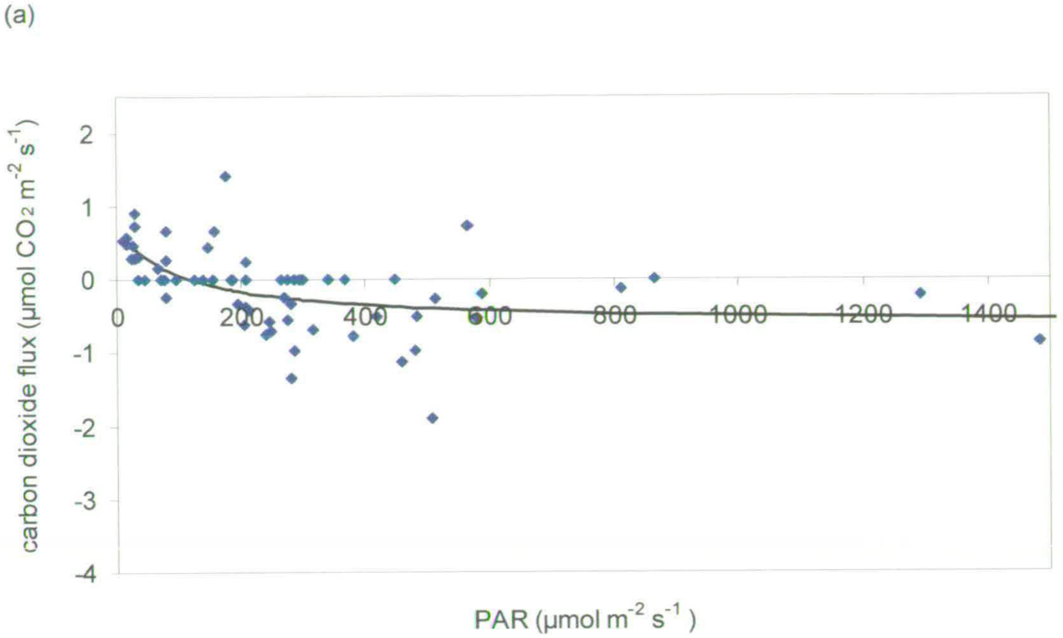
Table 4.3: Coefficients for non-rectangular hyperbola light response curve and regression equations for carbon dioxide fluxes (μmol CO_2 m^{-2} s^{-1}) in the light and dark and methane flux (μmol CH_4 m^{-2} s^{-1}) with associated R^2 adjusted, P values and degrees of freedom (*df*). Q_{10} values are given for 7 and 17 °C.

Flux type	**Site**	*ε*	*A_{max}*	*R_d*	**R^2 adj %**	**P value**	***df***
CO_2 light non-rectangular hyperbola	Nam	0.0126	1.34	0.71	30.9	< 0.001	67
	Sletill	0.0063	2.24	0.52	38.6	< 0.001	70
	Leir	0.0030	3.68	0.15	28.7	< 0.001	70
	Maol Donn	0.0056	3.68	0.57	51.7	< 0.001	78
	Drain	0.0218	4.17	1.42	66.4	< 0.001	117
	Regression equation			**Q_{10}**	**R^2 adj %**	**P value**	***df***
CO_2 light log	Nam flux = 1.261 - 0.608*log PAR				28.2	< 0.001	67
	Sletill flux = 1.911 - 0.979*log PAR				37.1	< 0.001	70
	Leir flux = 1.426 - 0.837*log PAR				21.2	< 0.001	70
	Maol flux = 2.148 - 1.140*log PAR				41.7	< 0.001	78
	Drain flux = 3.947 - 2.029*log PAR				63.2	< 0.001	117
CO_2 dark linear	Nam flux = -0.087 + 0.106*soil temp			2.6	57.3	< 0.001	98
	Sletill flux = -0.162 + 0.088*soil temp			2.9	65.7	< 0.001	97
	Leir flux = -0.102 + 0.088*soil temp			2.7	38.3	< 0.001	102
	Maol flux = 0.036 + 0.063*soil temp			2.3	38.3	< 0.001	110
	Drain flux = -1.017 + 0.161*soil temp			15.6	39.5	< 0.001	118
CO_2 dark exponential	Nam flux= 0.3762*exp(0.0891*soil temp)			2.4	49.9	< 0.001	98
	Sletill flux= 0.1285*exp(0.1515*soil temp)			4.6	68.6	< 0.001	97
	Leir Flux = 0.2294*exp(0.1163*soil temp)			3.2	35.4	< 0.001	102
	Maol flux = 0.2432*exp(0.0943*soil temp)			2.6	33.4	< 0.001	110
	Drain flux = 0.0896*exp(0.1904*soil temp)			6.7	37.6	< 0.001	118
CH_4 linear	Nam = -0.00042 + 0.00048*soil temp			2.6	17.9	< 0.001	98
	Sletill = -0.00204 + 0.00215*soil temp			2.6	55.1	< 0.001	97
	Leir = -0.00195 + 0.00078*soil temp			3.2	16.1	< 0.001	102
	Maol = -0.00106 + 0.00434*soil temp			2.5	55.1	< 0.001	109
	Drain = 0.01828 - 0.00026*soil temp			-	0.0	0.63	118
	Drain = 0.01766 + 0.00003*water table			-	1.7	0.082	118
CH_4 exponential	Nam flux = 0.0015*exp(0.0988*soil temp)			2.7	14.9	< 0.001	98
	Slet flux = 0.0065*exp(0.0986*soil temp)			2.7	42.5	< 0.001	97
	Leir flux = 0.0016*exp(0.1241*soil temp)			3.4	13.4	< 0.001	102
	Maol flux = 0.0131*exp(0.1092*soil temp)			3.0	50.4	< 0.001	110
	Drain flux = 0.0153*exp(($3.147*10^{-11}$)*soil temp)			- -	0.0	1.0	118
	Drain flux = 0.0018*exp(0.0018*water table)				0.19	0.08	118

Table 4.3 shows results of the various regression techniques applied shown are; non-rectangular hyperbola coefficients, regression equations, R^2 adjusted values and p values and degrees of freedom for site CO_2 flux and PAR, site CO_2 flux in the absence of light and soil temperature and CH_4 flux and soil temperature (also water table at the drain site). The resulting responses of Table 4.3 are illustrated in Figures 4.2, to 4.7 for the five sites. All regressions were significant ($p < 0.001$) except the relationship between drain site CH_4 flux and soil temperature and water table where

no relationship could be determined using both regression models but a near significant result was obtained for water table and CH_4 flux ($p = 0.08$) but the resulting R^2 adjusted value is very low implying large amount of variation remains unexplained. For CO_2 in the light the non-rectangular hyperbola model overall explains more of the variation as indicated by higher R^2 values but is only slightly better in explaining the variation in flux values at Nam Breac and Sletill than the log linear response. Relatively higher values of A_{max} for the Drain site and Leir and Maol Donn indicate higher light saturation values, hence more carbon fixation at high PAR. The lowest A_{max} figure associated with Nam Breac would appear to indicate that this site attains a more rapid maximum rate for photosynthesis and is likely to fix less carbon. However, A_{max} may be somewhat underestimated because there are fewer data points for higher values of PAR especially at Nam Breac and Leir. The dark respiration figures for the non-rectangular hyperbola indicate that Drain site has the value for dark respiration which suggests than in the absence of light this site may be a larger source of CO_2 than the other sites. Nam Breac also has a relatively higher rate of dark respiration an effect which may compound the lower maximum rate of assimilation for this site leading to an overall relatively lower carbon fixation. However, as the data are not corrected for temperature and significant relationships were identified with air temperature and CO_2 flux in some sites in Table 4.2, interpretation should be cautious.

For CO_2 in the dark only Sletill has an improved R^2 using the exponential approach in all other cases the linear model explains a larger proportion of the variation. For CH_4 fluxes the linear model appears a better explanatory model of the variation than the exponential as indicted again by higher R^2. Q_{10} values for the sites indicate a hierarchy do not appear to correspond between the two different models for CO_2 in the dark and CH_4 but the Drain site is consistently higher than the other sites for CO_2 dark and Leir has the highest Q_{10} for both models for CH_4.



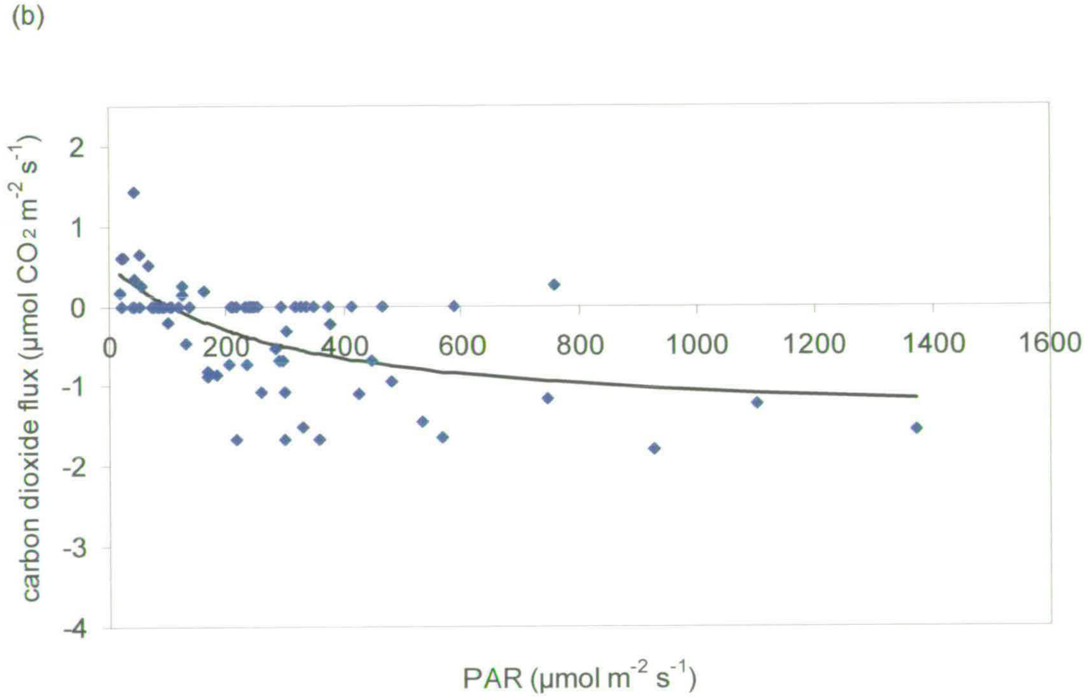
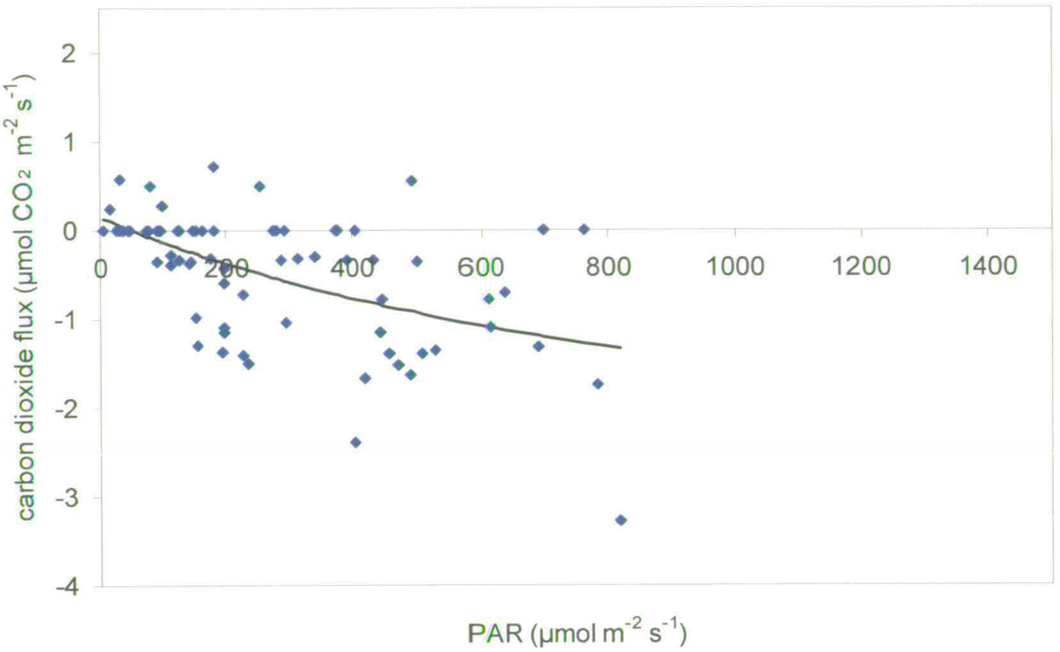


Figure 4.2: CO_2 light non rectangular hyperbola, light response curve by site. For details of analysis see Table 4.3. CO_2 flux is expressed in µmol CO_2 m^{-2} s^{-1} and PAR, µmol m^{-2} s^{-1}. (a) Nam Breac, (b) Sletill, (c) Leir, and (d) Maol Donn (e) Cross Lochs Drain. Continued overleaf.

(c)



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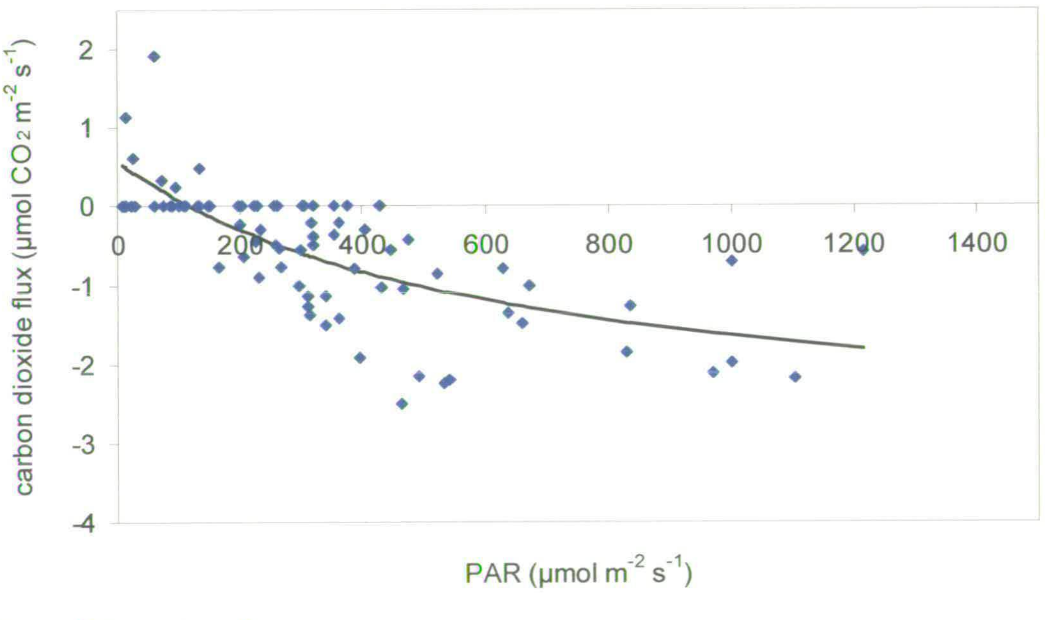
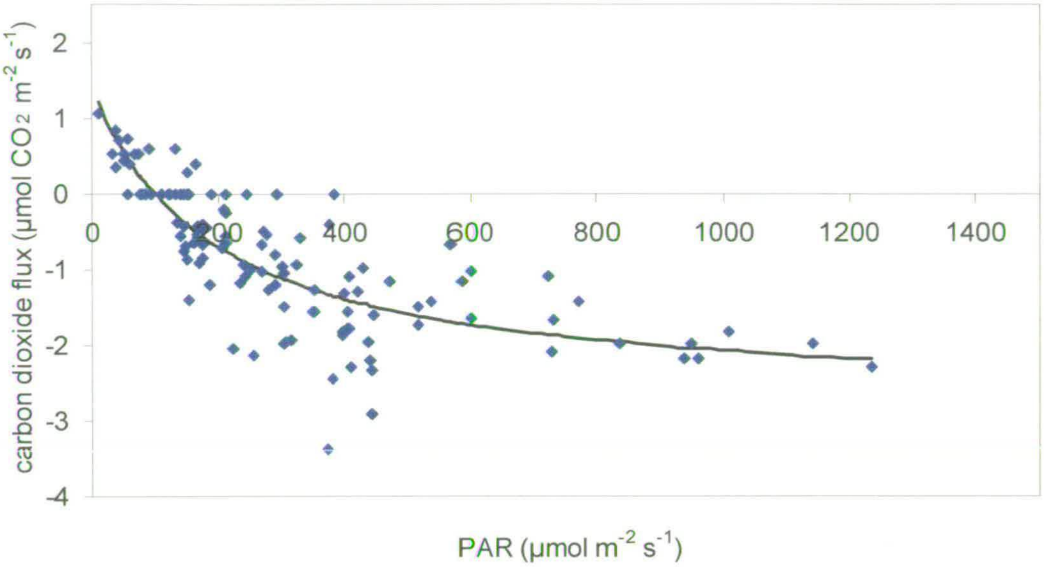


Figure 4.2 continued.

(e)



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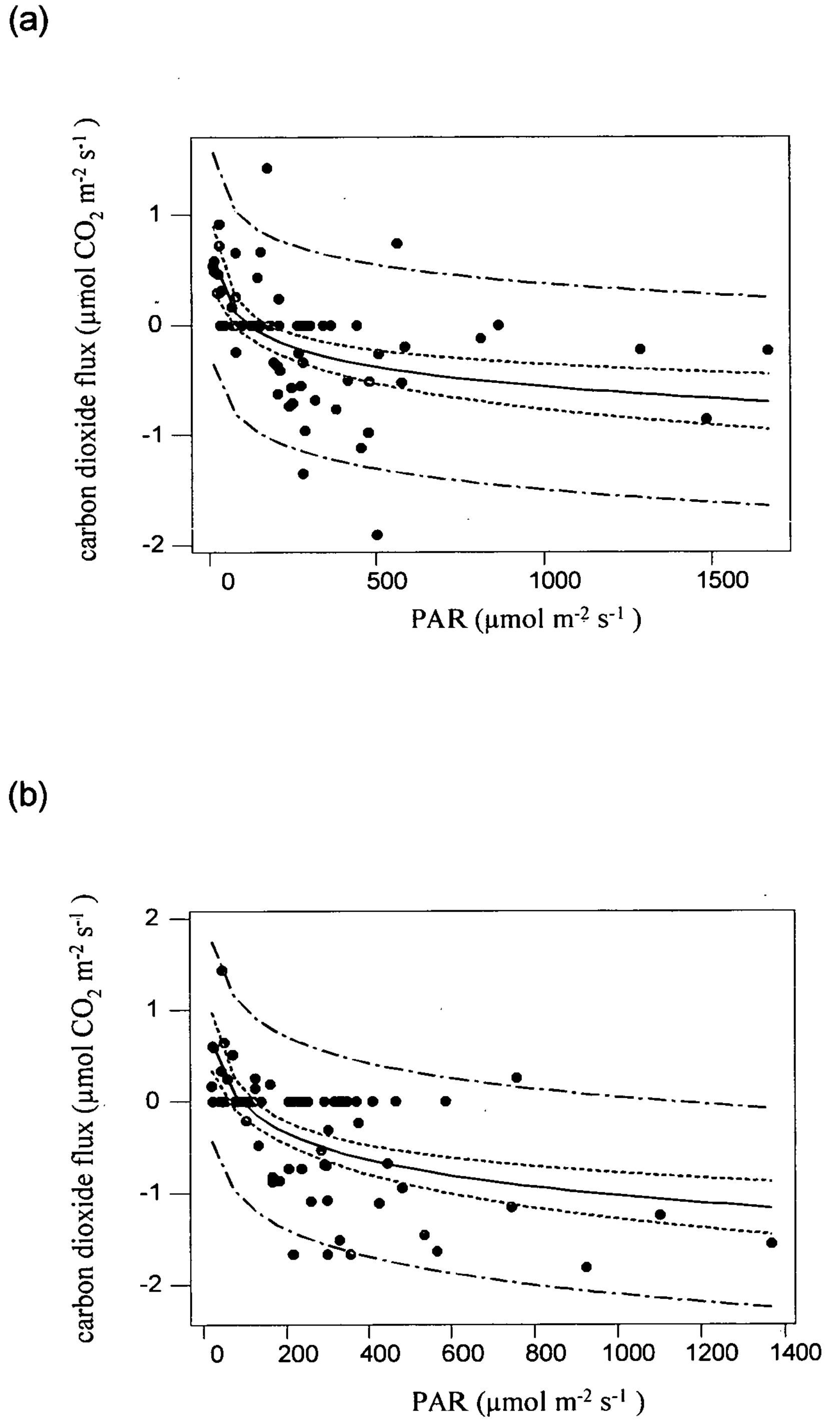


Figure 4.3: CO_2 light log linear regression by site. For details of regression analysis see Table 4.3. CO_2 flux is expressed in μmol CO_2 m^{-2} s^{-1} and PAR, μmol m^{-2} s^{-1}. (a) Nam Breac, (b) Sletill, (c) Leir, and (d) Maol Donn (e) Cross Lochs Drain. Blue dashed lines represent prediction intervals and red dashed lines represent 95% confidence intervals of the regression line. Continued overleaf.

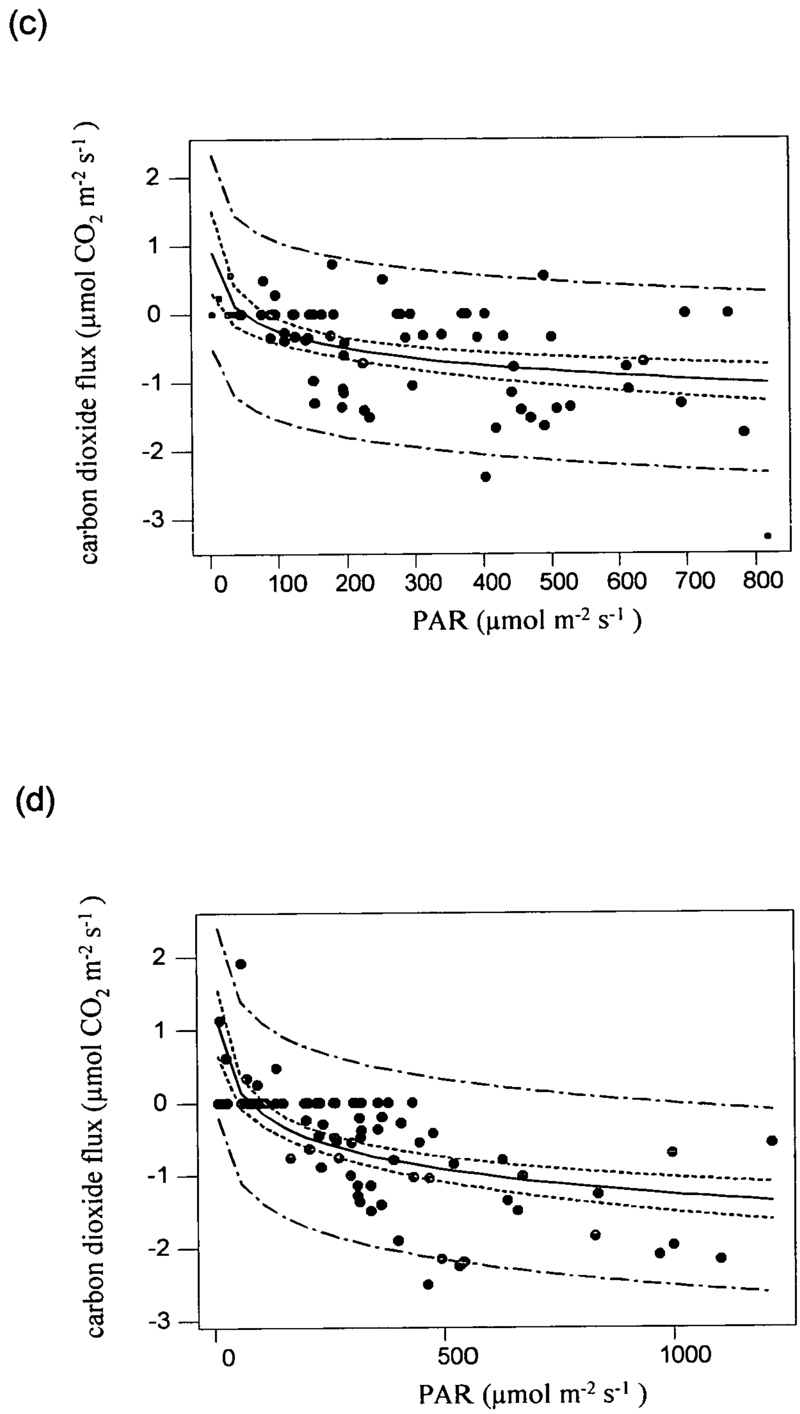
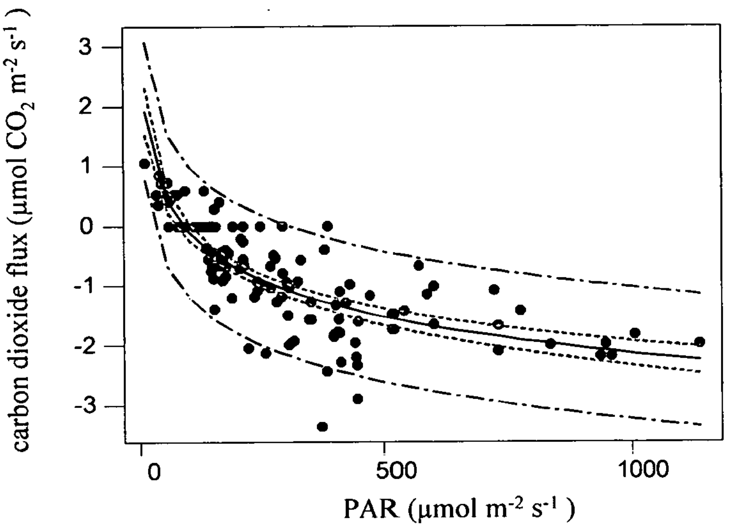


Figure 4.3 continued.

(e)



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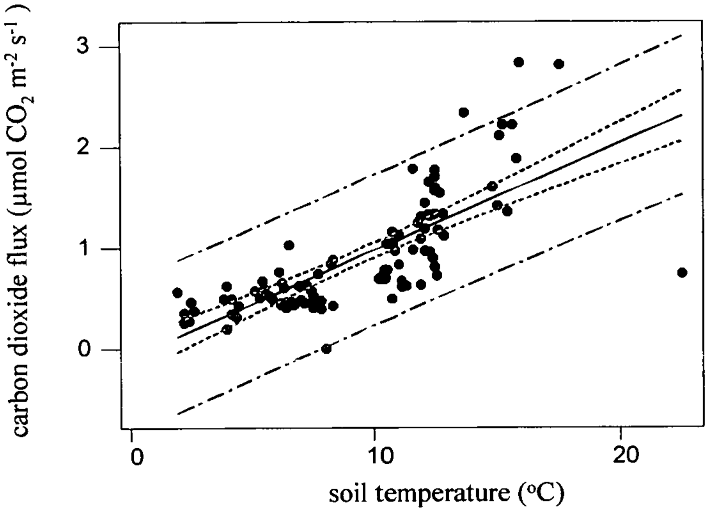
(a)



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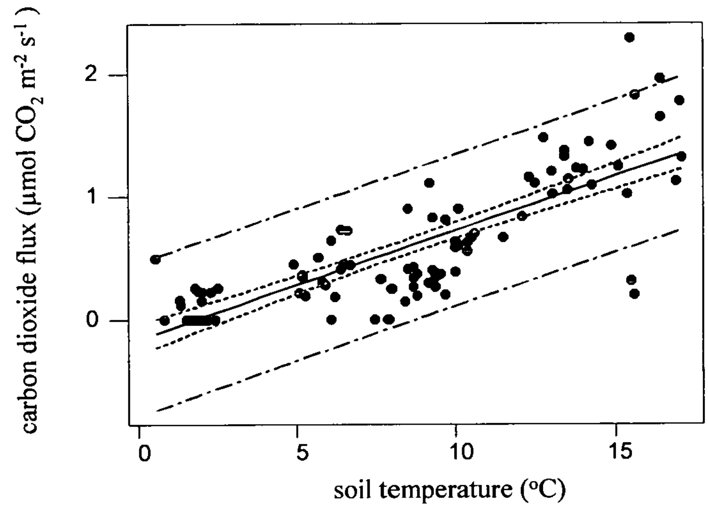
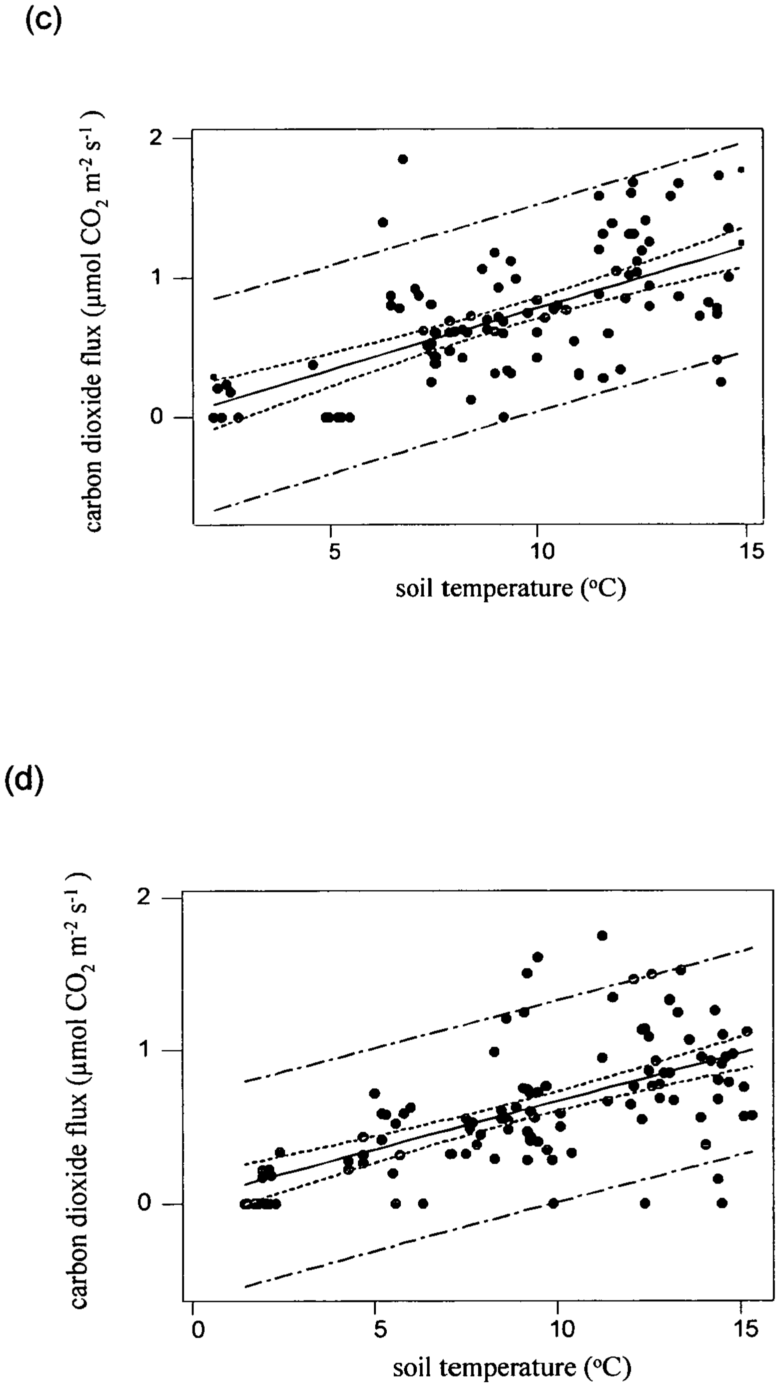


Figure 4.4: CO_2 dark response linear regression by site. For details of regression analysis see Table 4.3. CO_2 flux is expressed in μmol CO_2 m^{-2} s^{-1} and soil temperature °C. (a) Nam Breac, (b) Sletill, (c) Leir, and (d) Maol Donn (e) Cross Lochs Drain. Blue dashed lines represent prediction intervals and red dashed lines represent 95% confidence intervals of the regression line. Continued overleaf.



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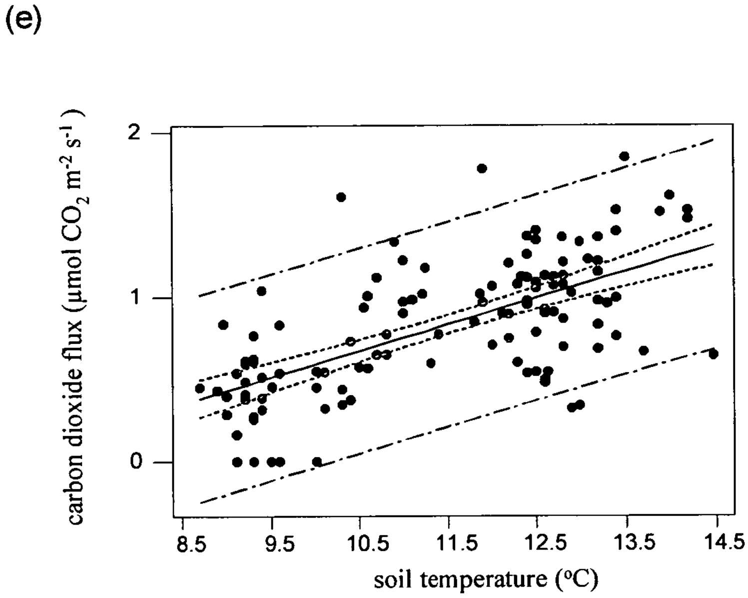

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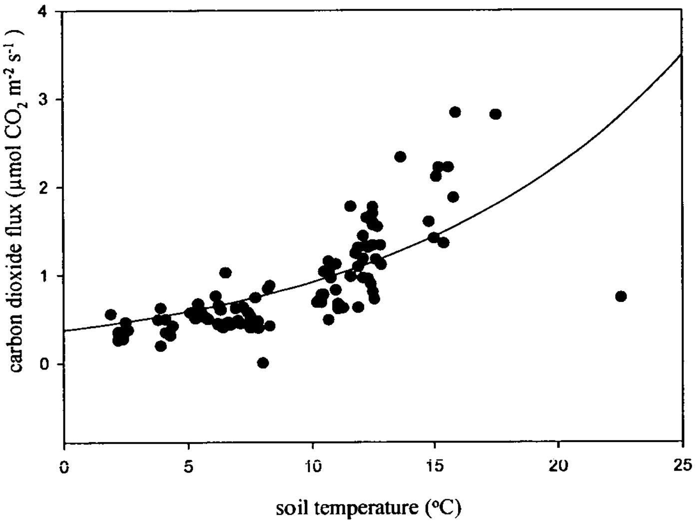
(a)



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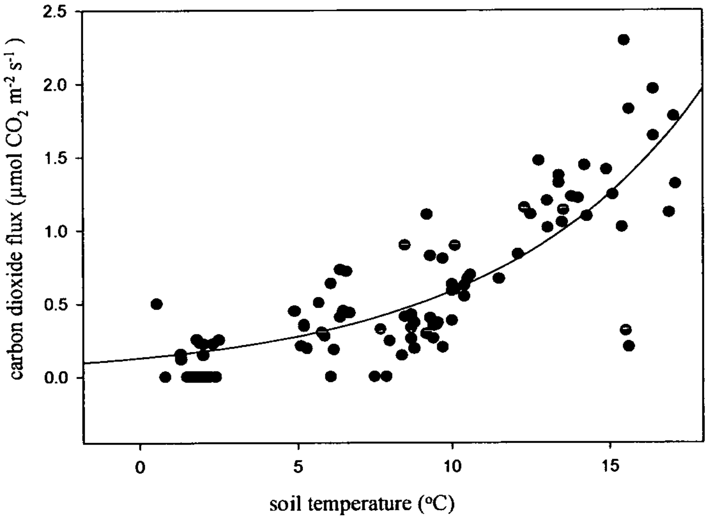
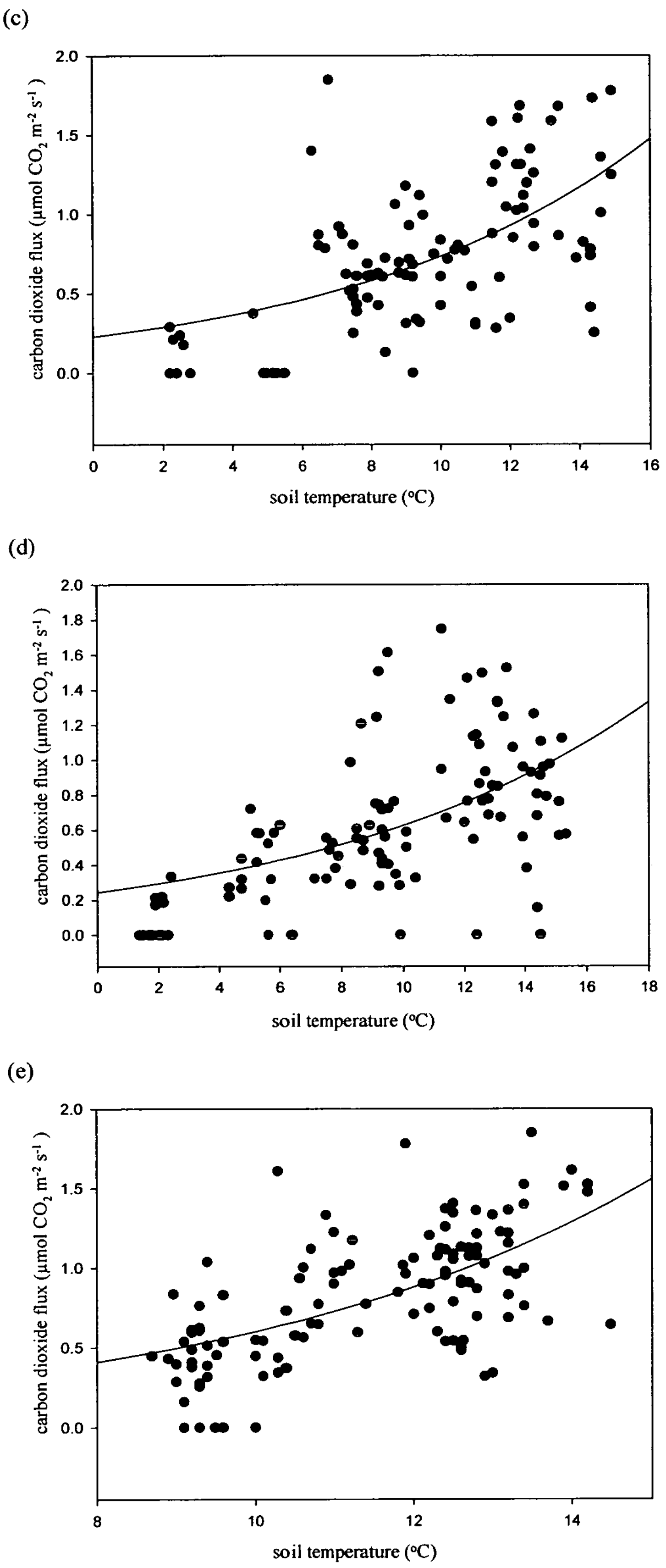


Figure 4.5: CO$_2$ dark exponential regression by site. For details of regression analysis see Table 4.3. CO$_2$ flux is expressed in μmol CO$_2$ m^{-2} s^{-1} and soil temperature °C. (a) Nam Breac, (b) Sletill, (c) Leir, and (d) Maol Donn (e) Cross Lochs Drain. Continued overleaf.



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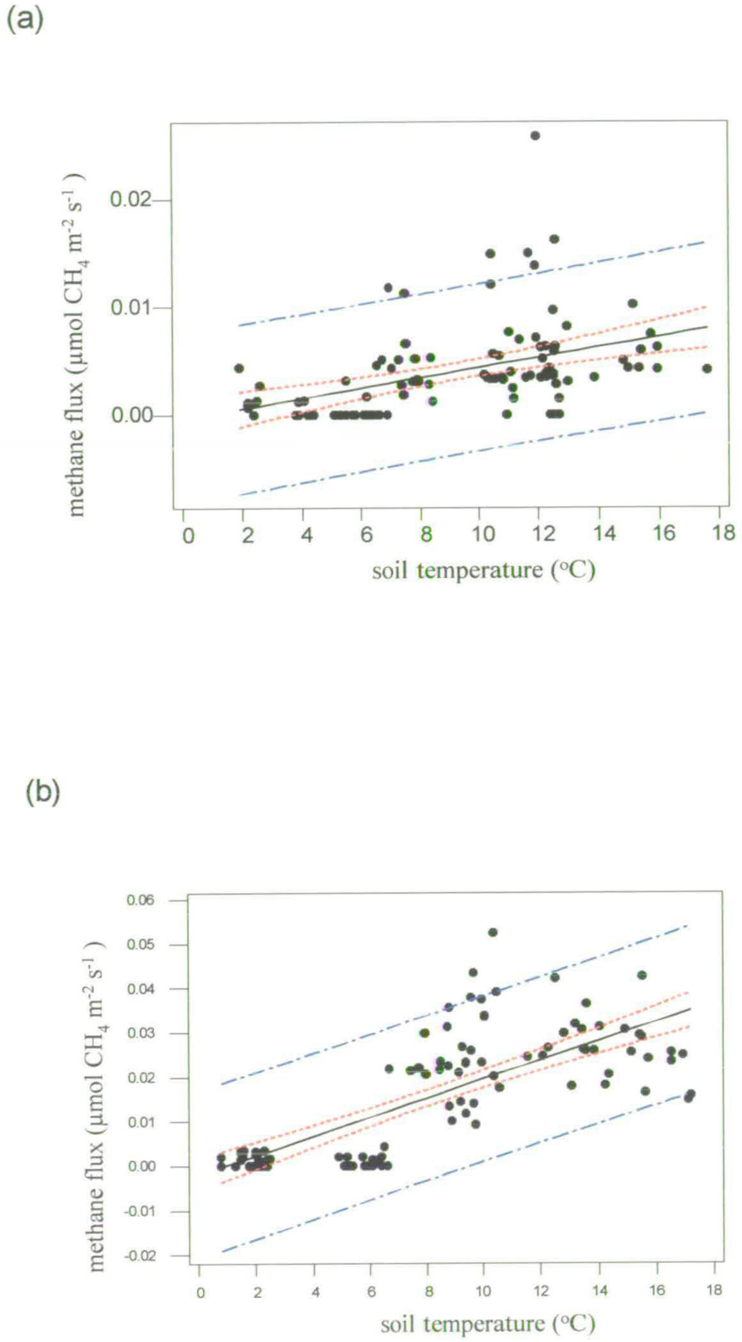
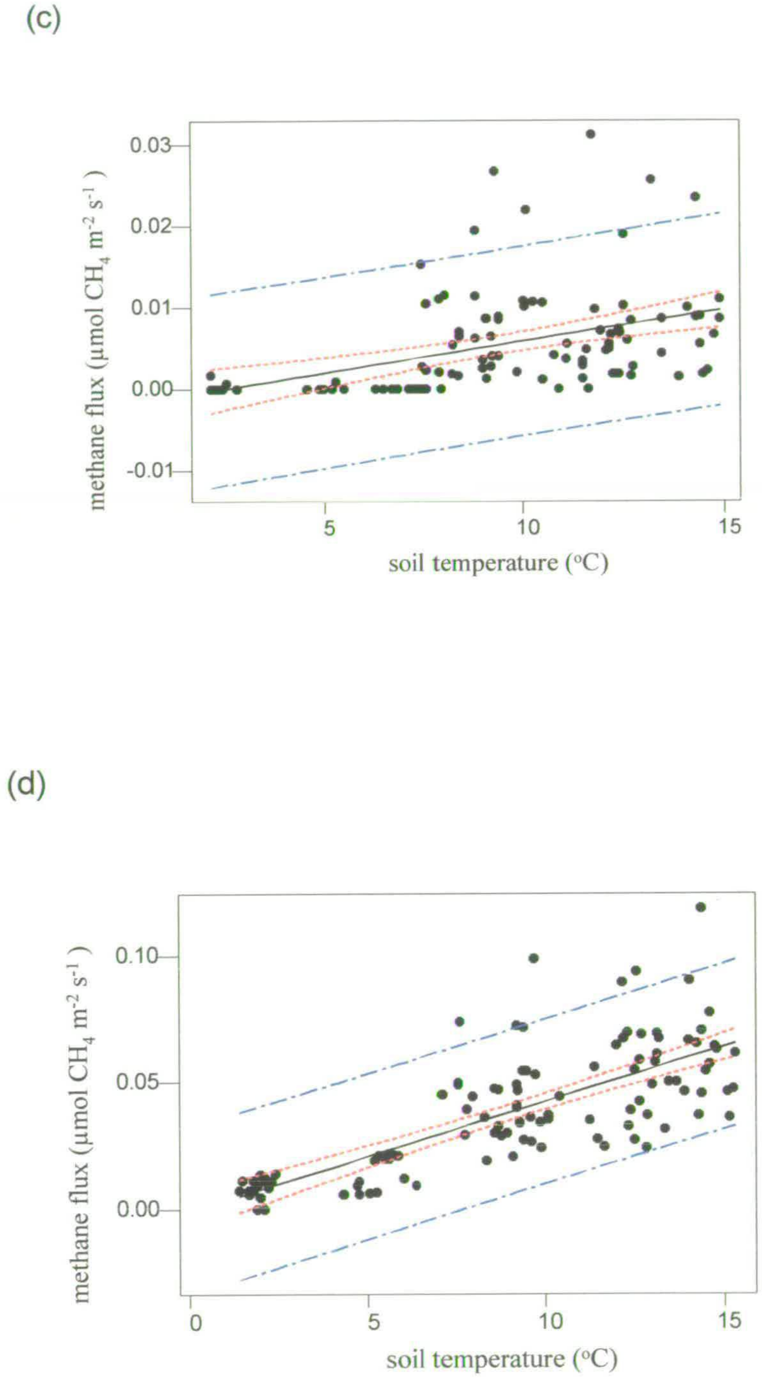


Figure 4.6: CH_4 soil temperature linear regression by site. For details of regression analysis see Table 4.3. CH_4 flux is expressed in μmol CH_4 m^{-2} s^{-1} and soil temperature °C. (a) Nam Breac, (b) Sletill, (c) Leir, and (d) Maol Donn. Blue dashed lines represent prediction intervals and red dashed lines represent 95% confidence intervals of the regression line. Continued overleaf.



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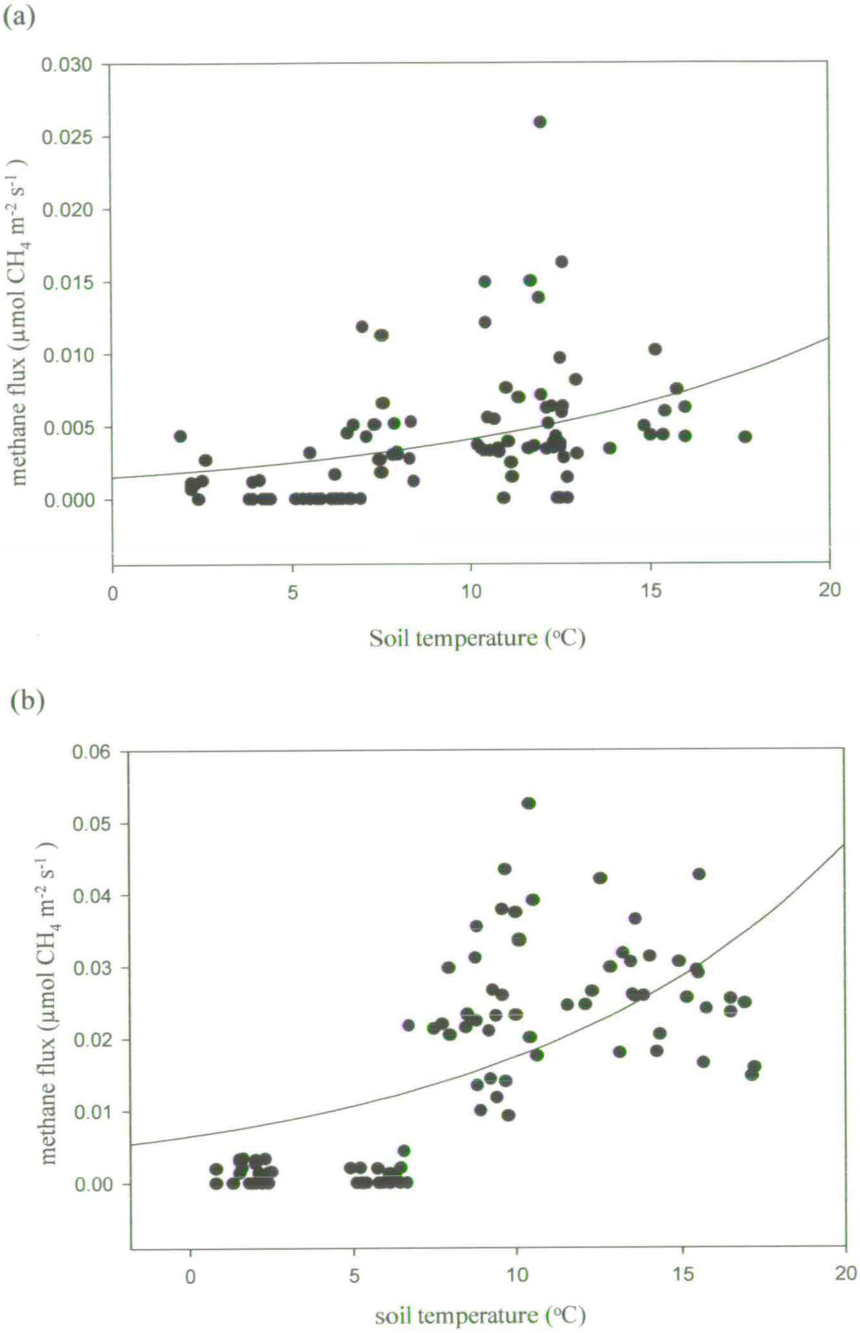
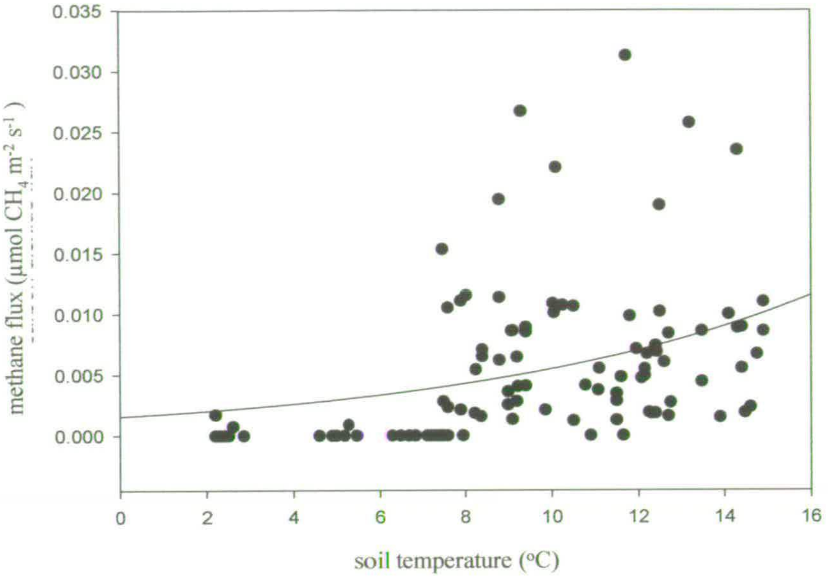


Figure 4.7: CH_4 soil temperature exponential regression by site. For details of regression analysis see Table 4.3. CH_4 flux is expressed in µmol CH_4 m^{-2} s^{-1} and soil temperature °C. (a) Nam Breac, (b) Sletill, (c) Leir, and (d) Maol Donn. Continued overleaf.

(c)



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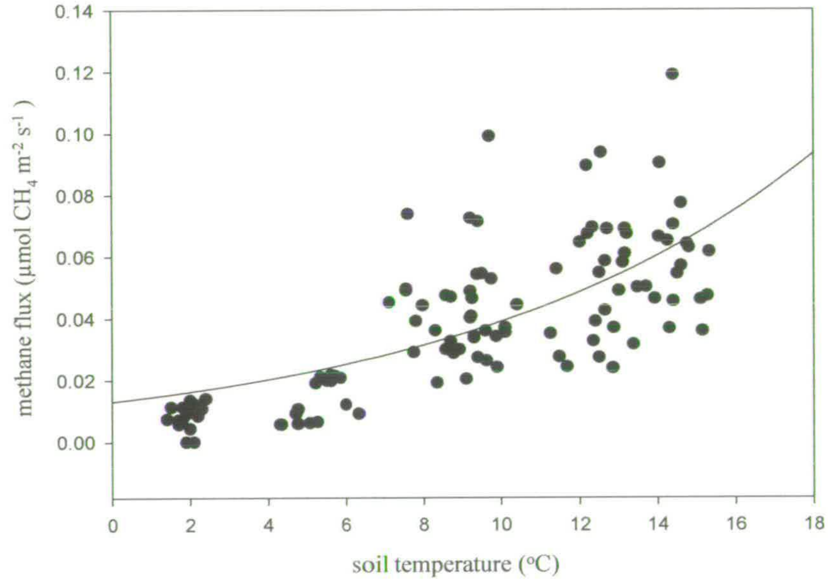

Figure 4.7 continued.

4.5 Discussion

It is noticeable from Figures 4.2 to 4.7 and Table 4.3 (R^2 adjusted values) that there is much within site variation that remains to be explained. Even though temperature and water table effects were not always significant they will contribute something to residual variation so expression as a single term will necessarily show some scatter. Some of this may also be due to differences between individual plots within a site.

Plots undoubtedly contain different species in different proportions in terms of plants (see Chapter 3) and possibly micro-organisms, leading to different potential rates for photosynthesis, respiration, and methane production and oxidation within sites. Other unaccounted variation will be methodological and random in nature.

Although Figures 4.2, to 4.7 and Table 4.3 indicate much scatter and points lie outside the prediction intervals, there is still some indication that there may be some differences in gas flux responses to climate variables between sites (statistical analyses of site differences are investigated in Chapter 5).

For CO_2 in the light the non-rectangular hyperbola model explains more of the variation as indicated by higher R^2 values and the coefficients of this analysis indicate that Nam Breac may be less able to fix carbon through photosynthesis and has a higher dark respiration rates than the other sites as indicated by high ε and lower A_{max} figures. Dark respiration terms may also have some consequence in terms of management. Managed sites (Drain) or damaged sites (Nam Breac has higher proportion of bare peat) appear to exhibit higher dark respiration rates. The rates in the linear model analysis of CO_2 in the dark also show the same systematic site pattern as identified by the non-rectangular hyperbola, although this pattern is not repeated in the exponential models. In linear model terms, CO_2 flux in light conditions the drain site appears to have the highest response per unit of light, Nam Breac appears to have the lowest rate and the remaining three sites all appear to have a similar response. In terms of the linear response of CO_2 respired in the absence of light; Nam Breac has the steepest response per unit temperature then the drain site, Sletill and Leir have the same response and Maol Donn has the lowest rate. The CH_4 temperature responses for the remaining 4 sites seem to show marked differences although much of this may be explained through differences in water table and penetrometer readings rather than by management, see Figure 5.3 above. The fact that the drain site appears to have a greater rate of carbon assimilation in the light may also be a consequence of this disturbance resulting in vegetation of species that fix carbon relatively faster such as *Molinia caerulea* (Jefferies, 1915, 1916). Increased CO_2 respiration and fixation rates have also been detected in drained peatlands in other studies (e.g. Minkkinen et al., 2002).

The higher R^2 values for the linear model for both CO_2 and CH_4 regressions suggest that the linear model is slightly better in explaining variation than the exponential model. However, interpretation of Q_{10} values is complicated by the dependence of Q_{10} on the temperature values upon which it is based for the linear model. The changing value of Q_{10} with different values of temperature is also present in other models commonly used for Q_{10} determination, such as the Arrhenius model, however, for the exponential models Q_{10} is constant (Fang & Moncrieff, 2001). The values reported in this study appear to be within the range reported by other studies. An exponential model used for Finish peatlands estimated Q_{10} to range between 1.3 to 4.9 for CO_2 (Silvola et al., 1996) In Scotland a range between 2.7 to 39 were reported for CO_2 respiration in using an Arrhenius model (Chapman & Thurlow, 1998). Also in Scotland for CH_4 a range between 2.2 to 4.8 for different micro habitats has been reported again using an Arrhenius model (MacDonald et al., 1998). In terms of management effects, higher Q_{10} values are apparent for cut over peat (Waddington et al., 2001) and lower CO_2 Q_{10} in flooded compared with drained treatments have been reported (Hogg et al., 1992) this would appear to be in agreement with the results obtained here.

That water table was not identified as being a significant predictor of CH_4 flux except at Leir and the inability to detect a relationship between soil temperature and/or water table and CH_4 flux at the drain sites is puzzling since these are well known relationships (Martikainen et al., 1992; Bubier & Moore, 1994; Bubier, 1995; Bubier et al., 1995; Bergman et al., 1998; Hargreaves & Fowler, 1998; MacDonald et al., 1998; Bergman et al., 1999a; Hughes et al., 1999; Kettunen et al., 1999). At Leir one of the plots is a *Racomitrium lanuginosum* hummock with associated lower water tables this may help explain some of the apparent water table effect at Leir. The lack of a water table effect at the other sites may indicate that within site water table variability is low and that water table only becomes a significant predictor when between site variability is considered. Or it may be that the type of dip wells utilised here are not sensitive to smaller changes in water table. Water table and soil temperature effects at the drain site were not detectable in either model analyses or when analysing the drain site as a whole or when analysing the data separately i.e.

blocked, unblocked and in the centre between drains. This may indicate that physical disturbance caused by constructing drains, may have profoundly altered the mechanisms of CH_4 production. Although, studies have shown that drainage, especially for forestry, has reduced CH_4 emissions (Cannell et al., 1993; Roulet et al., 1993; Roulet & Moore, 1995; Langeveld et al., 1997; Minkkinen et al., 2002), there appear to be fewer studies addressing the mechanisms for this change beyond the statements of lower water tables. However, evidence from Canada and Finland indicates that drainage not only alters the production of methane within the peat profile (Minkkinen et al., 2002; Glatzel et al., 2004) but also affects the rate of potential methane production through the lack of adequate substrate for methanogenic bacteria (Galand et al., 2005). These authors hypothesise that the change in vegetation from sedge dominated bog to forest causes a change in the amount of carbon exuded from roots reaching the deeper layers of the peat, as trees tend to concentrate exudates in the top 30 cm. The Cross Lochs drains were created in the late 1970's - 1980's and blocked in 1996. If the action of creating the drains has profoundly affected the microbial community then it may indicate that the effects of disturbance may persist for decades and are not changed by merely raising the water table. However, this is only one site and it may be an anomalous finding.

Other approaches than those used here to model responses of gas flux to environmental variables exist, such as the Arrhenius equation which is frequently used for the relationship between soil decomposition and temperature (Chapman & Thurlow, 1998; MacDonald et al., 1998; Fang & Moncrieff, 2001; Davidson & Janssens, 2006). However, reducing complex biological processes like photosynthesis, respiration and methanogenesis using these models is undoubtedly an abstract method. Many of these models seem to give useful parameters such as the dark respiration values of the hyperbola models and the Q_{10} values given above or the activation energies of the Arrhenius approach. However, the interpretation of these types of parameters here is difficult since these models have more meaning when conditions such as temperature and light are controlled. The field measurements made in this study had no such controls and a degree of confounding introduced from differences in temperature, light, plant species, plant biomass, microbial communities, water status, nutrient status, enzymes, reactant substrate availability exists. The main question though is not over the choice of model to explain the relationship but whether the relationship as indicated by the same model is consistently different between sites. This would then tend towards the general conclusion that management (as indicated by site) does affect carbon flux environment relationships. Since sites do appear to be different. As the central tenet of this thesis is that carbon fluxes are affect by management, this would appear to be corroborative evidence. However, as stated above field data are confounded, firm conclusions should not be drawn and examination of the management question awaits statistical testing in Chapter 5.

4.6 Conclusions

- Significant relationships between gaseous fluxes and climate variables were found.
- Both log linear and non-rectangular hyperbola models for CO_2 in the light explained a good deal of the variation in site datasets but the hyperbola model consistently explained more variation.
- Linear and exponential model comparison for CO_2 flux in the dark indicates that the linear model explains more variation than the exponential model.
- However, these did not always follow theoretically predicted relationships: water table did not consistently predict of methane flux and at the drain site neither soil temperature nor water table could be related to carbon dioxide flux in the dark.
- Suggested reasons for these departures from theory include a lack of within site variability in water table and possible damage to microbial communities following drainage disturbance.
- Management may explain some of the differences in responses but as the data are confounded by other factors e.g. temperature in light responses these effects are not explicit.

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Chapter 5: Does management influence the gaseous carbon fluxes of blanket bog?

5.1 Introduction

That peatlands have been carbon sinks in the past is demonstrated by the size of the store of carbon within peat. The maintenance and enhancement of global carbon sinks and stores has been called for by The Intergovernmental Panel on Climate Change (IPCC) (Watson et al., 2000). Estimates of carbon accumulation rates in peatlands since the end of the last glaciation are available from peat core evidence and range from 6 to 31 g C m^{-2} yr^{-1} (Clymo et al., 1998; Robinson & Moore, 1999, 2000; Vitt et al., 2000; Turunen et al., 2001; Turunen et al., 2002; Byrne et al., 2004). Increasingly, questions are being asked about the responses of peatlands and other ecosystems to climate change, other anthropogenic disturbance and the interactions between these (Garnett et al., 2000; Turetsky et al., 2002; Byrne et al., 2004; Hulme, 2005; King, 2005). Whether peatlands are carbon sinks at present, or will continue to be in the face of climate change and other anthropogenic disturbance, is uncertain; nonetheless maintaining this carbon store is important. Although peat accumulation rates are informative for detailing the past, the usefulness of the peat core technique for present and future carbon balances is limited (Byrne et al., 2004). Other techniques such as measuring primary productivity and vegetation structure by clipping or harvest techniques have long been used (Forrest, 1971; Summerfield, 1973; Tyler et al., 1973; Forrest & Smith, 1975; Moore, 2002) but these techniques often underestimate the below ground productivity and also takes no account of methane production, a significant contributor to peatland greenhouse gas budgets. Thus the measuring of gaseous carbon fluxes by chamber techniques and more recently by eddy-covariance have become popular and have now been in use in peatlands for decades (Clymo & Reddaway, 1972; Bubier et al., 1992; Verma et al., 1992; Oechel et al., 1993; Bubier et al., 1995; Choularton et al., 1995; Beverland et al., 1996; Beverland et al., 1997; Hargreaves & Fowler, 1998; MacDonald et al., 1998; Alm et al., 1999; Hargreaves et al., 2003). The resulting data provide information on present fluxes and can used for deriving models for predicting future dynamics. The majority of these peatland studies have been conducted in continental Europe the northern United States and Canada.

In the UK there have been fewer studies on gaseous fluxes from peatlands and the majority of these have concentrated on methane (see Chapter 2). This is despite the fact that UK peatland ecosystems are not only the primary carbon store but also the UK's largest semi-natural ecosystem (Lindsay, 1995). Notwithstanding the doubtful existence of any 'pristine' peatlands in the UK due to the prevalence of centuries of management, the responses of UK peatlands to climate change are likely to be somewhat different to those of the peatlands of Continental Europe, Canada and the USA (Chapter 2). All of the UK's blanket bog is subjected to varying degrees of management practices such as burning, grazing as well as drainage. Although the practice of moor-gripping (drainage) has reduced since the withdrawal of grants, there are still many active open drains (grips) present on blanket bog areas today. However, the areas of UK blanket bog under different management types are difficult to gauge (Chapter 1).

5.2 Study aims

Here the question of whether management affects the gaseous carbon fluxes of blanket bog is addressed using carbon dioxide and methane gaseous flux data from the north of Scotland.

These results are used not only to examine differences between sites of differing management but also to speculate on ecosystem responses to certain climate change scenarios for the UK.

5.3 Methods

5.3.1 Site Description

Details of site descriptions and management are given in Chapter 3.

5.3.2 Vegetation Characterisation

Details of sampling methods for vegetation are given in Chapter 3.

5.3.3 Gas Flux Measurements

Details of sampling methods for gas flux measurements are given in Chapter 4

5.3.4 Statistical Analyses

Missing Data

Climate variables (photosynthetically active radiation (PAR), air temperature and relative humidity) between June 2004 and October 2004 were lost due to computer failure. These were replaced in the general linear modelling (GLM) analysis by data obtained from linear regression models derived from data obtained at Kinbrace Meteorological Station approximately 10 km south of Forsinard. The data were modelled using Kinbrace data as predictors of Forsinard data for air temperature and relative humidity over the period when the two datasets were congruent. Missing data were then calculated from the regression equation for each relationship over the period for when the data is missing. No significant relationship between Kinbrace light and Forsinard PAR could be determined. However, Forsinard air temp and relative humidity were significant predictors of Forsinard PAR, therefore modelled values of air temp and relative humidity from the Kinbrace regression were used to model Forsinard PAR over the missing period. This does however create non-independence in the climate data, therefore, datasets for 2003-4 and 2005 were analysed separately. All regression equations are given in the Appendix. For graphical exploration of sites L, M and N (see below), the Kinbrace values for light and temperature are used not modelled values.

Determination of the effects of management on gaseous carbon fluxes was conducted using a general linear model in Minitab 13. Four datasets were tested; main sites 2003-4 and 2005 (Leir, Maol Donn, Nam Breac and Sletill); fire site (burnt and unburnt); and the Cross Lochs drain site (blocked, unblocked and centre; between the two drains). The fire site was burnt in early 2004 (possibly March) with the unburnt area just outside the burnt area; however, the general area in which the fire site is located is subjected to burning. The drains were cut in the 1970's and 80' and blocked in 1996 (Rout, 1996). The tests were performed separately for CO_2 fluxes in the light, CO_2 fluxes in the dark and CH_4 fluxes, as indicated in Table 5.1, giving a total of 12 different analyses. In each model the focus of interest was directed towards determining whether site effects and site climate variable interactions were present. A further stratification of the main sites dataset into damage and undamaged sites was also carried out. This essentially splits off the 'damaged' Nam Breac site from the 'undamaged' Leir, Maol Donn and Sletill sites. This damage test should ideally have been made between sites but the test had no power ($F_{1,2}$) therefore was tested against plot variation only when site effects were not significant. 2003-4 main site CO_2 dark and CH_4, 2005 main sites CH_4 and fire site CO_2 dark flux data, were square root transformed to improve homogeneity of variance. PAR data were Log_{10} transformed to improve linearity. Flux and climate data for the main Forsinard sites and sites L, M, and N are explored graphically.

Table 5.1: General linear model terms. Plot (Site) indicates plots nested within site. Main sites are Nam Breac, Sletill, Maol Donn and Leir.

Datasets tested	Main sites 2003-4		
	Main sites 2005		
	Fire: Unburnt vs Burnt		
	Drains: Unblocked vs Blocked vs Centre		
Response	CO_2 light flux	CO_2 dark flux	CH_4 flux
Fixed Factors	Site	Site	Site
	Plot (Site)	Plot (Site)	Plot (Site)
	Month	Month	Month
Co-variables	PAR + air temp + RH	soil temp + water table	soil temp + water table (except Drain site only soil temp)

The Relationships between vegetation and water table penetrometer data and gas flux linear regression responses slopes were analysed with Redundancy Analysis (RDA) and implemented in Canoco 4.5 software.

Tentative carbon balance modelling was derived from single term, response models developed between field gas flux data and PAR, air temperature and soil temperature in Chapter 4 using Minitab 13; regression equations are given in Table 4.3 (Chapter 4). The carbon fluxes were then predicted over one year using values for air temperature, soil temperature and a derived PAR from 2004 climate data from the Kinbrace station at hourly periods. Daytime fluxes were calculated using relationships between PAR and carbon dioxide flux with a low temperature threshold of 5 °C whereby no CO_2 fixation is possible. Night time fluxes were derived from the relationship between soil temperature and carbon dioxide flux. Soil temperature was derived from the relationship between Kinbrace air temperature and Forsinard soil temperature, see Appendix. PAR was calculated as 47% of the Kinbrace global irradiance values (Blackburn & Proctor, 1983) daily mean modelled PAR and actual daily mean PAR at Forsinard showed a reasonable agreement (R^2 adj = 76.3%, n = 47 days, see Appendix). Methane fluxes were calculated from the relationship between methane flux and soil temperature with soil temperature derived as above. All other summary statistics and graphical plots were generated using Minitab 13 and Microsoft Excel 2000 software.

5.4 Results

5.4.1 Management effects on gaseous carbon fluxes

5.4.1a Statistical analyses using GLM

Table 5.2: Summary of effects and interactions analysed using general linear modelling for CO_2 light, CO_2 dark and CH_4 fluxes with associated p values and degrees of freedom (df) for sites in the Forsinard and Dorrery Nature Reserve. Statistically significant effects are highlighted in bold. AT = air temperature, PAR = photosynthetically active radiation, RH = relative humidity and ST = soil temperature.

Dataset	CO_2 Light Effect P value (df)	CO_2 Dark Effect P value (df)	CH_4 Effect P value (df)
Main Sites 2003-4	Site.AT 0.098 (3)	Site.ST 0.749 (3)	**Site.ST < 0.001 (3)**
	Site.RH 0.059 (3)		Site.WT 0.614 (3)
	Site.PAR 0.350 (3)		
	Site 0.776 (3)	**Site 0.005 (3)**	Site 0.0184 (3)
	Damage 0.748 (1)		
Main Sites 2005	**Site.PAR 0.034 (3)**	**Site.ST 0.003 (3)**	**Site.ST 0.027 (3)**
	Site.AT 0.086 (3)		Site.WT 0.986 (3)
	Site.RH 0.659 (3)		
	Site 0.705 (3)	Site 0.493 (3)	Site 0.662 (3)
	Damage 0.476 (1)	Damage 0.186 (1)	
Fire	Site.AT 0.222 (1)	Site.ST 0.212 (1)	Site.ST 0.391 (1)
	Site RH 0.225 (1)		Site.WT 0.488 (1)
	Site.PAR 0.169 (1)		
	Site 0.402 (1)	Site	**Site 0.004 (1)**
Drain	Site.AT 0.688 (2)	Drain.ST 0.220 (2)	**Drain.ST 0.011 (2)**
	Site.RH 0.628 (2)		
	Site.PAR 0.905 (2)		
	Site 0.664 (2)	Drain	Drain 0.988 (2)

Sign convention negative fluxes denote uptake of the gaseous compound.Table 5.2 summarizes the results of the general linear modeling analysis, full details of the results including tables of sums of squares and F-ratio tests are given in the Appendix.

One significant interaction was detected between site and PAR in the CO_2 light 2005 main site data (Table 5.2) the lack of an interaction in the 2003-4 dataset may be in part due to modeled PAR data. Mean CO_2 flux rates in the light for 2005 are: Leir -0.64 μmol CO_2 m^{-2} s^{-1}, Maol Donn -0.85 μmol CO_2 m^{-2} s^{-1}, Nam Breac-0.28 μmol CO_2 m^{-2} s^{-1} and Sletill -0.70 μmol CO_2 m^{-2} s^{-1}. This indicates a lower CO_2 flux at the damaged site of Nam Breac and suggests that this site response to PAR results in less CO_2 fixation. Site effects were detected in the 2003-4 CO2 dark data but no soil temperature interaction, conversely site effects are not apparent in 2005 CO_2 dark flux but significant site soil temperature interaction is present. Back transformed means of the 2005 data for Leir 0.49 μmol CO_2 m^{-2} s^{-1} Maol Donn 0.41 μmol CO_2 m^{-2} s^{-1} Nam Breac 0.74 μmol CO_2 m^{-2} s^{-1} and Sletill 0.25 μmol CO_2 m^{-2} s^{-1} suggest that the interaction between soil temperature and dark CO_2 flux is likely to be more pronounced at the damaged site Nam Breac. A significant site soil temperature interaction was also detected for the main site 2003-4 CH_4 flux and this relationship is also evident in the 2005 main site data. Back transformed 2003-4 means for Leir 0.0021 μmol CH_4 m^{-2} s^{-1}, Maol Donn 0.027 μmol CH_4 m^{-2} s^{-1}, Nam Breac 0.0015 μmol CH_4 m^{-2} s^{-1} and Sletill 0.0064 μmol CH_4 m^{-2} s^{-1}, and the evidence of positive relationships from Chapter 4 would suggest that effect is positive and may be more pronounced in Maol Donn and have the least impact at Nam Breac.

At the fire site there is a significant site effect on CH_4 fluxes but no other relationships were detected. Although the mean flux values are confounded by soil temperature and water table the mean flux values for the burnt site of 0.0264 μmol CH_4 m^{-2} s^{-1} compared with the unburnt site of 0.0072 μmol CH_4 m^{-2} s^{-1} suggesting that the burnt site emits more methane.

At the drain site there is also only one significant interaction between drain and soil temperature for CH_4 fluxes. However examination of residual plots for this analysis (see Appendix) reveal a slight wedge shape to the residuals versus fit plot indicating heterogeneity of variance. This significance of this interaction must therefore be treated with caution. Mean water table below the peat surface at the drain site for the study duration were; - 65 cm (9.4 SE) for the blocked drain, - 118 cm (7.0 SE) for the centre and - 64 cm (8.1 SE) for the unblocked drain.

5.4.1b Graphical exploration of Main Sites and Sites L, M and N

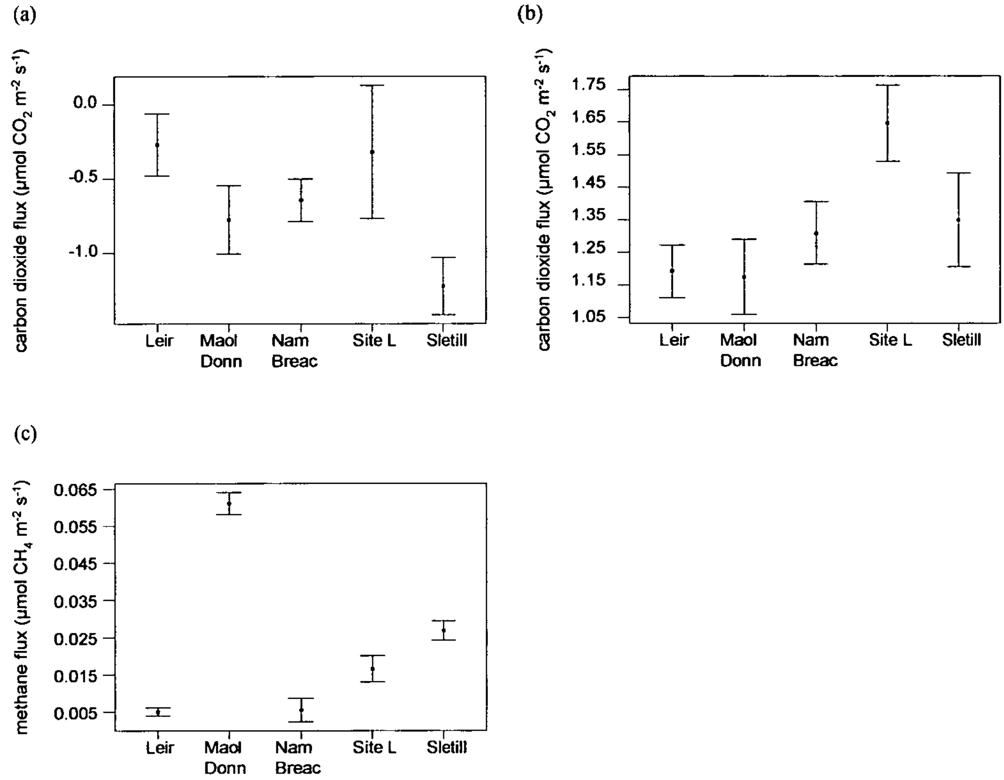

Figure 5.1: Mean (+/- SE); (a) carbon dioxide flux in the light (μmol CO_2 m^{-2} s^{-1}) (b) carbon dioxide flux in the dark (μmol CO_2 m^{-2} s^{-1}) and (c) methane flux (μmol CH_4 m^{-2} s^{-1}), at main sites and site L in July 2004. Sign convention: negative denotes uptake.

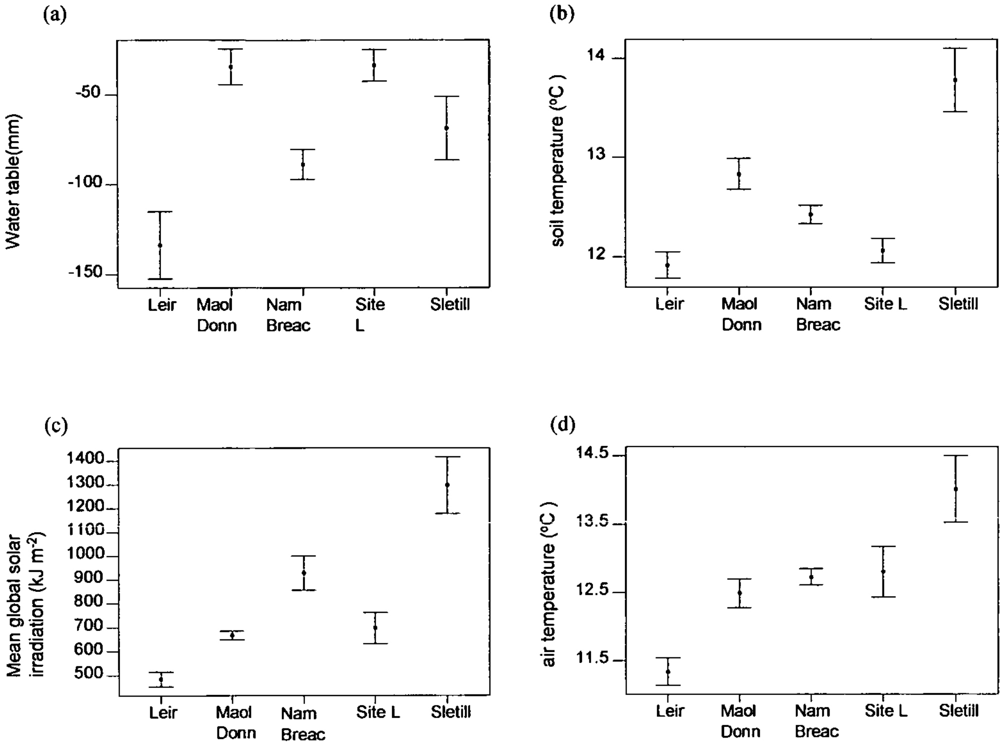

Figure 5.2: Mean (+/- SE); (a) water table (mm), (b) soil temperature (°C) at main sites and site L in July 2004, and (c) mean global solar irradiation (kJ m^{-2}) and (d) air temperature (°C) from Kinbrace Weather Station.

Figure 5.1 and 5.2 detail the gaseous fluxes and selected climate variables for the main sites and site L during July. These figures show that for carbon dioxide flux in the light Sletill seems to have a higher mean rate of fixation than any of the other sites; this is in conjunction with higher mean global solar irradiation and air temperature. The error bars of Site L appear to be the largest of any site and span the Maol Donn, Leir and Nam Breac values. Site L air temperature is similar to Nam Breac and Maol Donn and global solar radiation levels similar to Maol Donn. Therefore from the available data, Site L may have a similar response to light as the other sites in terms of carbon dioxide flux.

In terms of carbon dioxide flux in the dark Site L has the highest mean flux all other sites are similar and error bars span each site. Soil temperature of Site L appears to be the second lowest implying that Site L has a higher rate of carbon dioxide flux in the dark than the other sites.

Methane fluxes apparently follow patterns in both water table and soil temperature with Maol Donn showing a larger mean flux than any other site. Site L has lower flux rates than Sletill but higher than Nam Breac and Leir but has lower soil temperature than Sletill but a higher water table. Methane fluxes give the impression of being concurrent with environmental controls of water table and soil temperature.

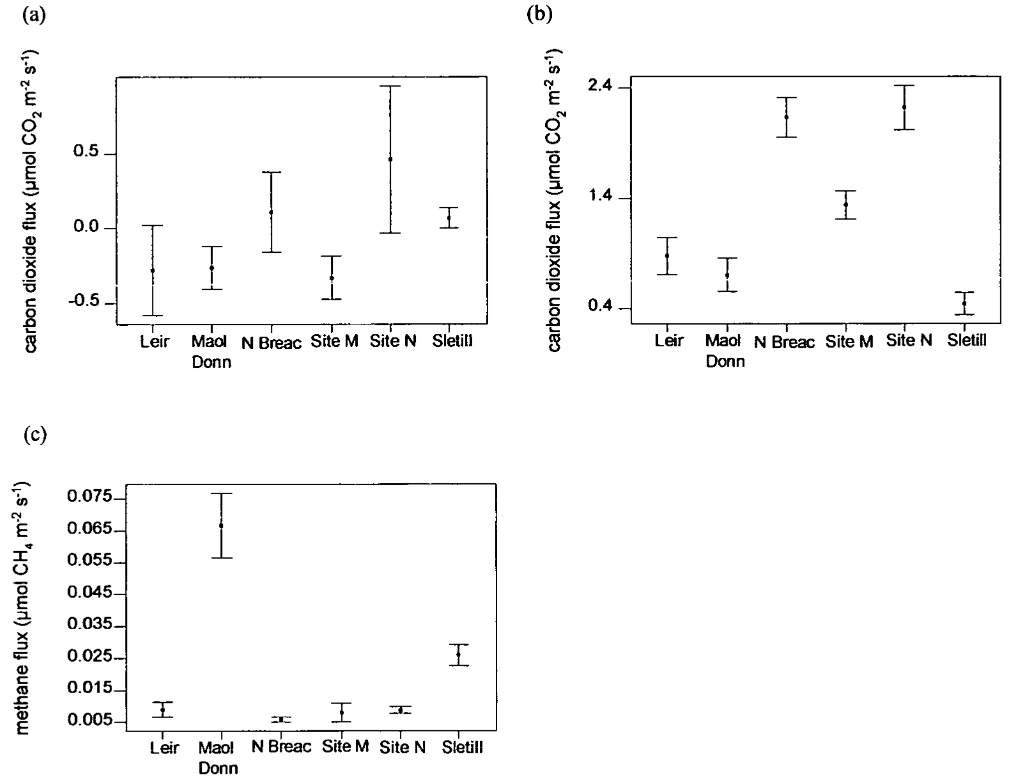

Figure 5.3: Mean (+/- SE); (a) carbon dioxide flux in the light (μmol CO_2 m^{-2} s^{-1}) (b) carbon dioxide flux in the dark (μmol CO_2 m^{-2} s^{-1}) and (c) methane flux (μmol CH_4 m^{-2} s^{-1}), at main sites and site L in July 2004.

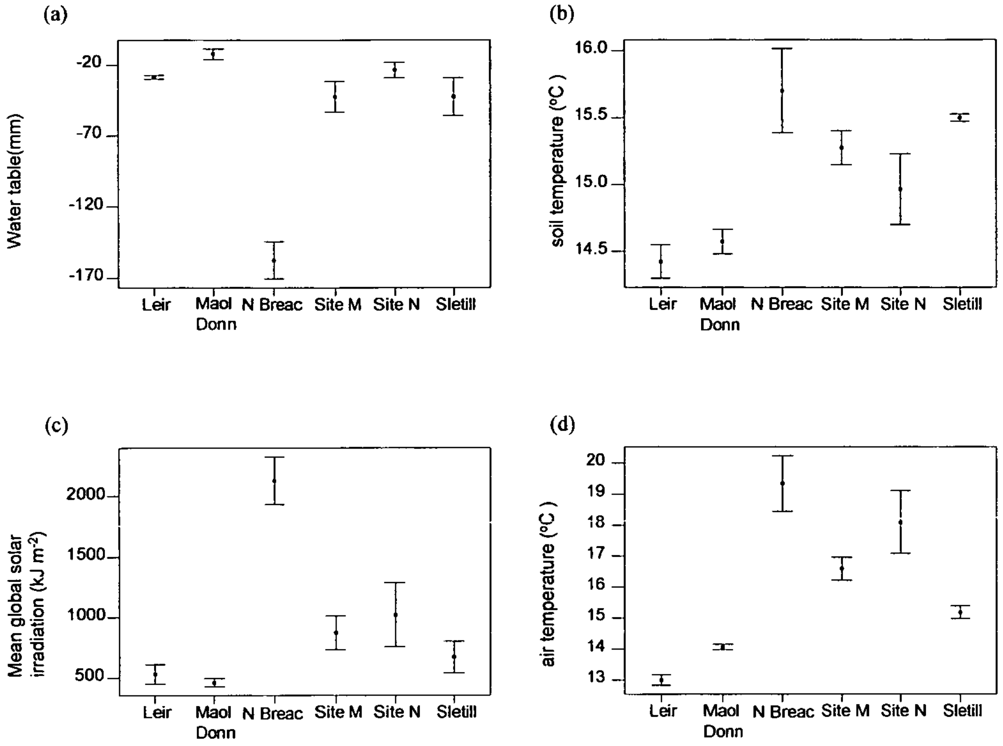

Figure 5.4: Mean (+/- SE); (a) water table (mm), (b) soil temperature (°C) at main sites and site L in August 2004, and (c) mean global solar irradiation (kJ m^{-2}) and (d) air temperature (°C) from Kinbrace Weather Station.

Figures 5.3 and 5.4 illustrate the gaseous fluxes and selected climate variables for August. Site N, Nam Breac and Sletill appear to show a loss of CO_2 in light conditions and Leir, Maol Donn and Site M appear to be sinks for CO_2 in the light. This is in contrast to climate conditions as Nam Breac has the highest light levels and air temperature, Site N, Sletill and Site M also appear to have higher light levels and air temperature. Therefore, climate variables do not appear to explain all the between site pattern in CO_2 flux in light conditions.

Nam Breac sites N and M appear to have higher mean rates of loss of CO_2 in the dark apparently following the pattern in soil temperature. However, Sletill has the lowest rate of CO_2 flux in the dark but a relatively high mean soil temperature. Therefore the climate does not appear to explain all the between site mean CO_2 fluxes in the dark illustrated in Figure 5.3.

CH_4 flux is highest again at Maol Donn as in July; Sletill has the next highest mean CH_4 flux, with the other three sites showing similar rates to each other. This would appear to follow water table and soil temperature patterns.

5.4.2 Relationship of vegetation to water table, penetrometer data and gas flux responses slopes

Figure 5.5 illustrates the results of a CCA ordination of vegetation in gas flux plots with penetrometer readings and the slopes for individual flux plot CO_2 and CH_4 flux linear regressions with PAR and soil temperature. Axes 1 and 2 account for 14.2% and 12.2% of species data respectively, and 31.6% and 27.2% of variation of species environment relations respectively. Restricted Mote Carlo permutations to account for pseudoreplication, and with drains samples removed because of unequal sample sizes, indicate the first axis is not quite significant ($p = 0.054$). This hints at differences between plots, statistical non-significance notwithstanding, there does appear to be some clustering of plots from the same site. Plots are separated mainly on the grounds of penetrometer readings at 5 and 10 cm with slope of methane flux and dark CO_2 flux on soil temperature being almost opposite in their reactions; water table is also highly correlated with CH_4 flux. Figure 5.6 shows the same ordination but with the species projected into ordination space. This shows some species that are correlated with particular conditions for example; bare peat is correlated with lower CO_2 light-PAR regression slopes. Also, species expected to be in association with high water table, e.g. *Sphagnum magellanicum,* correlate well with this and steeper CH_4 flux soil temperature responses. Highest rates of photosynthesis and respiration seem to be in tandem for example *Sphagnum capillifolium* has the steepest CO_2 – PAR response as well as a steep CO_2 soil temperature response in the dark, although *Myrica gale* appears to be associated with the steepest respiration soil temperature response.

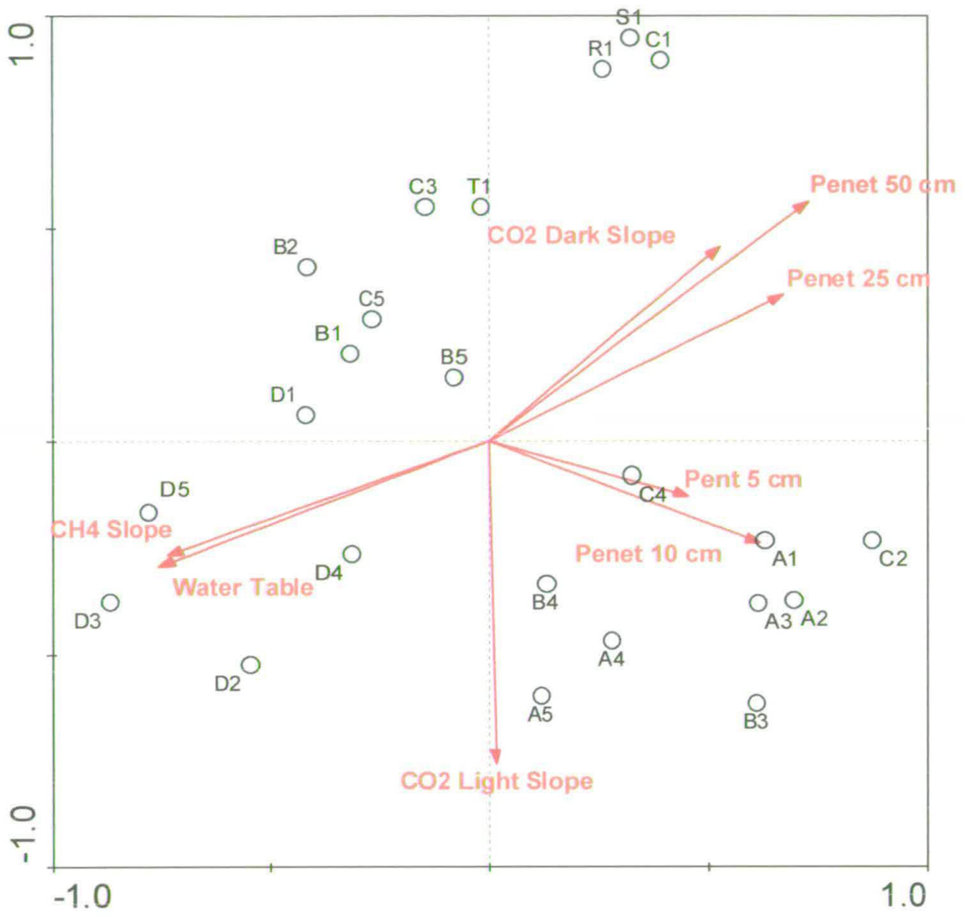

Figure 5.5: Axes 1 and 2 of CCA of species percentage cover data from plots used for gaseous flux measurements in nine peatland sites on the RSPB Forsinard Reserve showing samples. Plot codes are as in Table 5.2. Explanatory variables used are: mean peat penetrometer data at 5, 10, 25 and 50 cm mean water table, CO_2 light and dark and CH_4 regression slopes for individual plots. By convention CO_2 light is expressed as negative i.e. sink for carbon, therefore direction of arrow indicates decreasing rate of CO_2 assimilation in response to light. Axes 1 and 2 account for 14.2% and 12.2% of species data respectively, and 31.6% and 27.2% of variation of species environment relations respectively. See text for significance of Monte Carlo permutations.

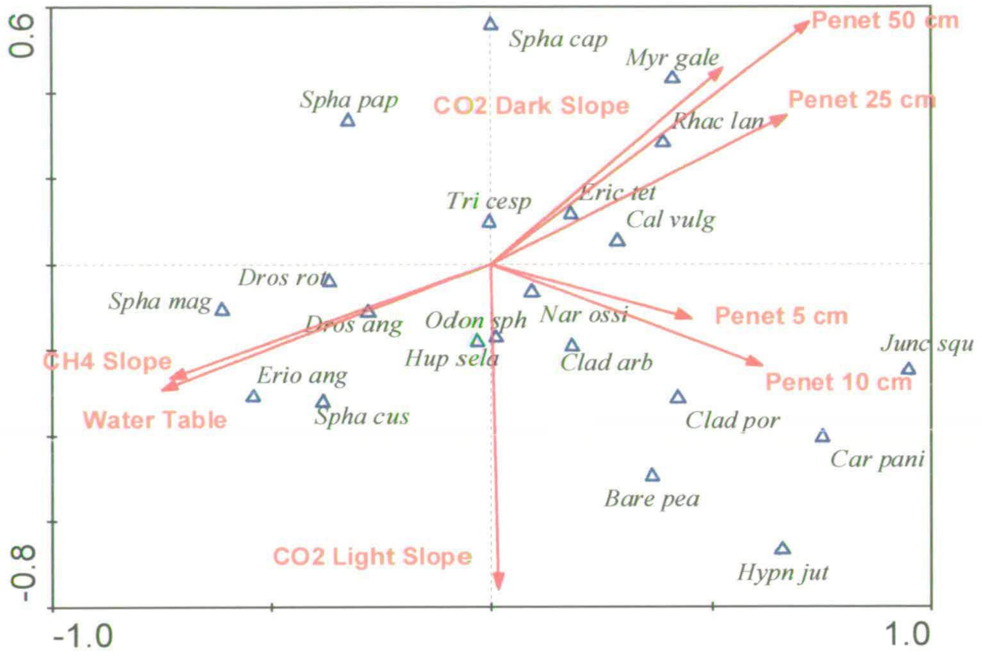

Figure 5.6: Axes 1 and 2 of CCA of species percentage cover data from plots used for gaseous flux measurements in nine peatland sites on the RSPB Forsinard Reserve showing species. Plot codes are as in Table 5.2. Explanatory variables used are: mean peat penetrometer data at 5, 10, 25 and 50 cm mean water table, CO_2 light and dark and CH_4 regression slopes for individual plots. By convention CO_2 light is expressed as negative i.e. sink for carbon, therefore direction of arrow indicates decreasing CO_2 light response. Axes 1 and 2 account for 14.2% and 12.2% of species data respectively, and 31.6% and 27.2% of variation of species environment relations respectively. See text for significance of Monte Carlo permutations.

5.4.3 Tentative carbon balances

The regression models of Table 4.3 in Chapter 4 are reproduced in Figures 5.7, to 5.10 without the raw data points. Here these regression equations are used to model carbon balances over the period of 1 year. Main consideration is given to log linear and non-rectangular hyperbola models for CO_2 fluxes in the light and because of better fit for linear models for CO_2 in the dark and CH_4 flux these are retained though some discussion of the use of exponential model is given.

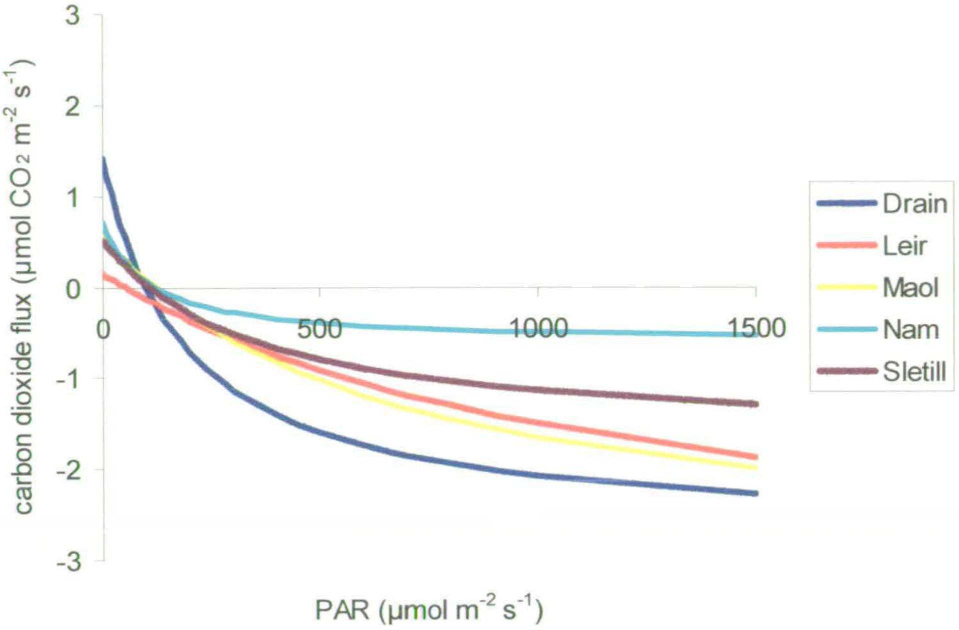

Figure 5.7: CO_2 light non-rectangular hyperbola responses by site. For details of regression analysis see Table 4.3. CO_2 flux is expressed in μmol CO_2 m^{-2} s^{-1} and PAR, μmol m^{-2} s^{-1}.

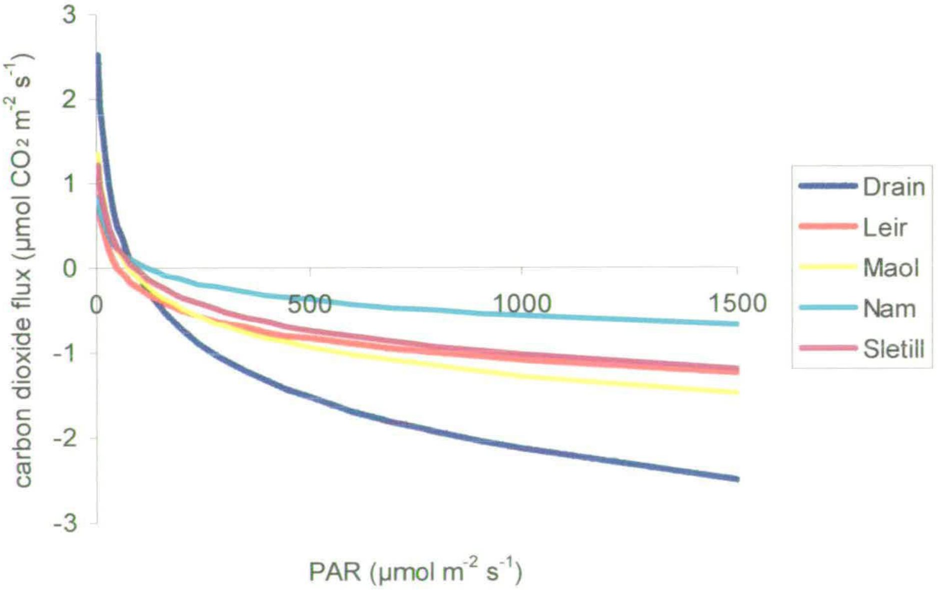

Figure 5.8: CO_2 light log linear regression responses by site, PAR plotted as anti log. For details of regression analysis see Table 4.3. CO_2 flux is expressed in μmol CO_2 m^{-2} s^{-1} and PAR, μmol m^{-2} s^{-1}.

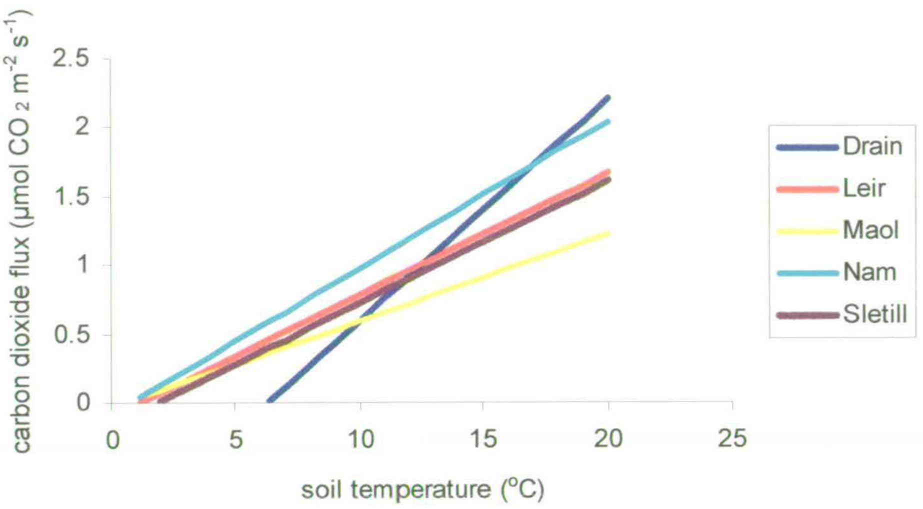

Figure 5.9: CO_2 in the dark soil temperature regression responses by site. For details of regression analysis see Table 4.3. CO_2 flux is expressed in µmol CO_2 m^{-2} s^{-1} and PAR, µmol m^{-2} s^{-1}.

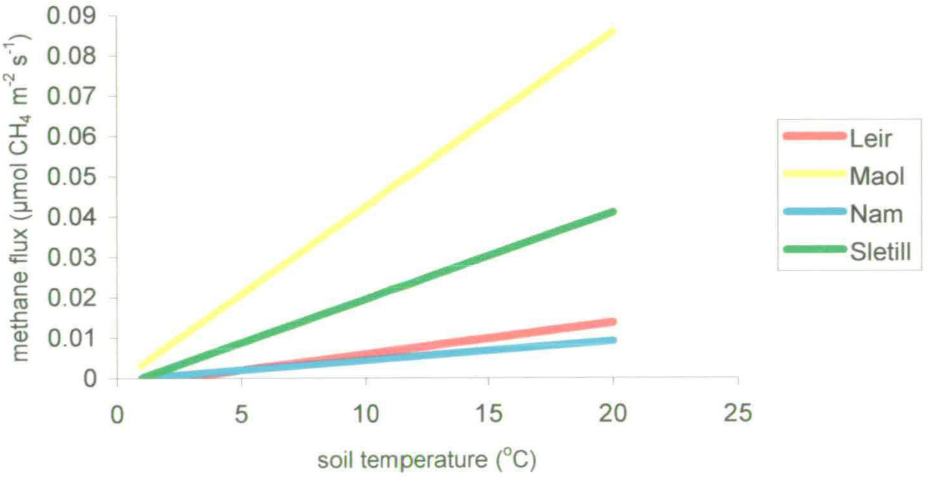

Figure 5.10 Methane soil temperature regression responses by site. For details of regression analysis see Table 4.3. CH_4 flux is expressed in µmol CH_4 m^{-2} s^{-1} and PAR, µmol m^{-2} s^{-1}.

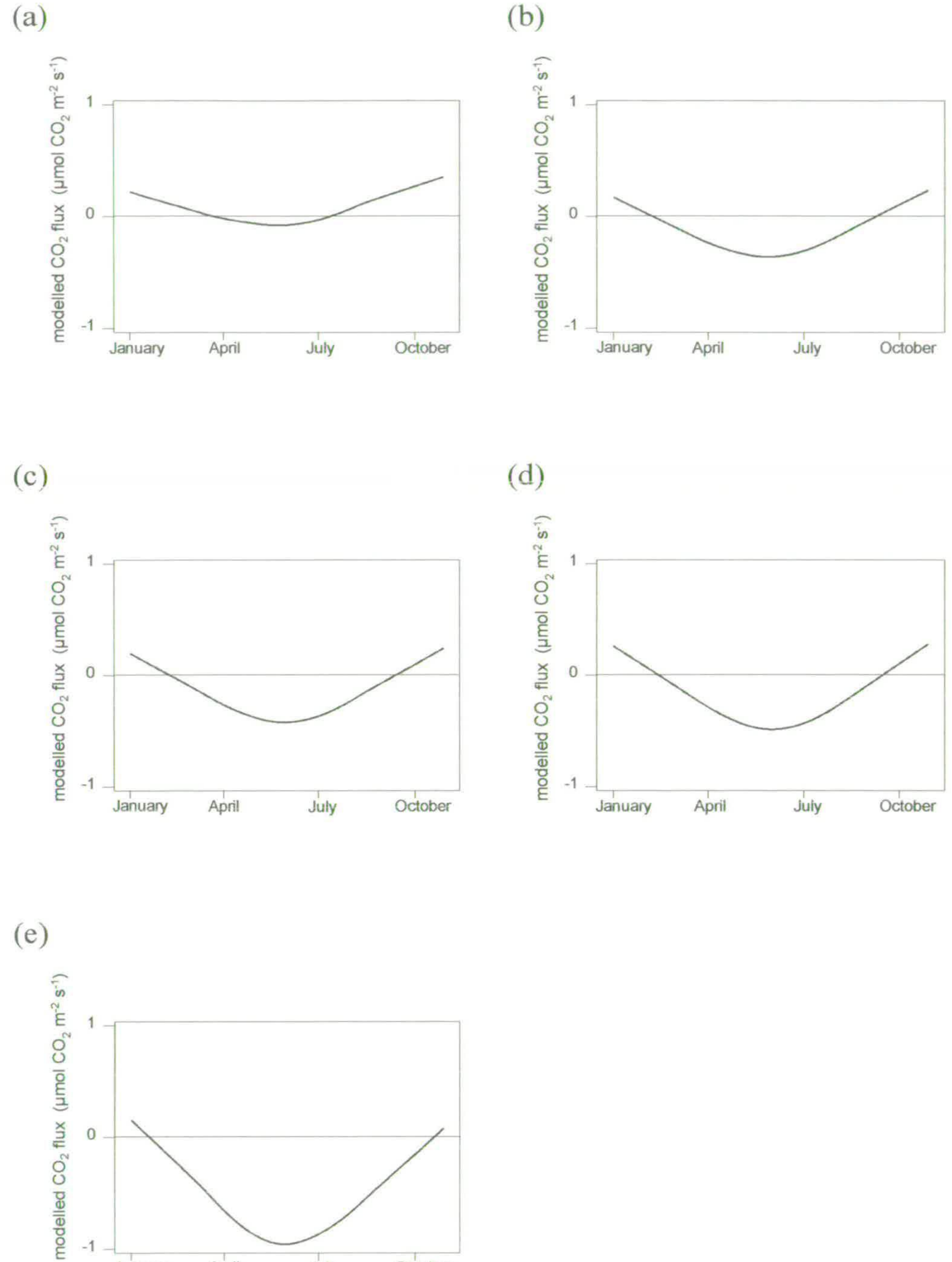

Figure 5.11: Modelled sum of carbon dioxide fluxes (μmol CO_2 m^{-2} s^{-1}) for Forsinard sites using linear regression equations in Table 4.3 and climate data from Kinbrace Meteorological Station 2004. Lines are lowess smoothers with 0.5 degree of smoothing and 2 steps. Modelled fluxes for; (a) Nam Breac, (b) Sletill, (c) Leir, (d) Maol Donn, and (e) Drains.

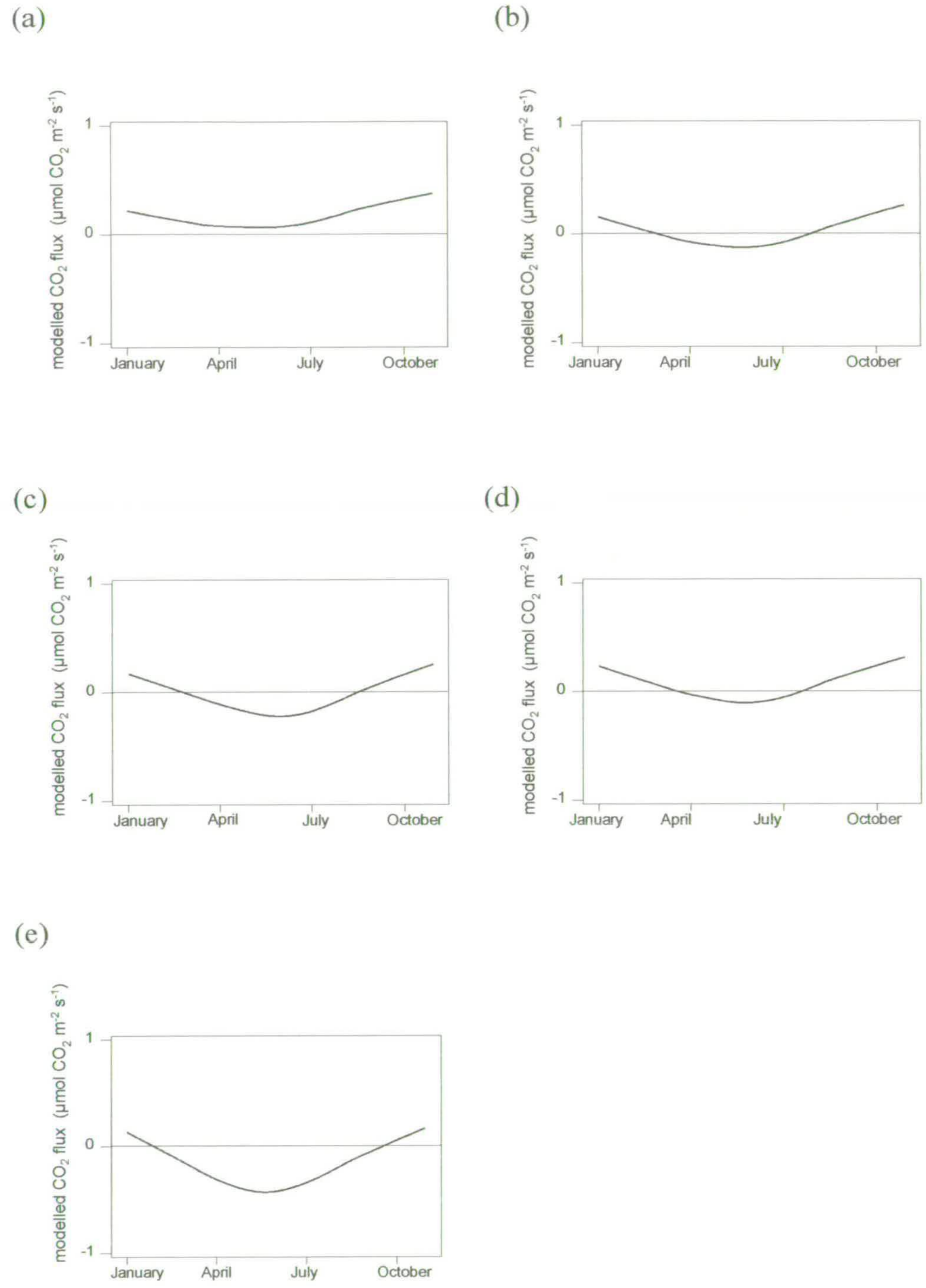

Figure 5.12: Modelled sum of carbon dioxide fluxes (µmol CO_2 m^{-2} s^{-1}) for Forsinard sites using non rectangular hyperbola and linear regression equations in Table 4.3 and climate data from Kinbrace Meteorological Station 2004. Lines are lowess smoothers with 0.5 degree of smoothing and 2 steps. Modelled fluxes for; (a) Nam Breac, (b) Sletill, (c) Leir, (d) Maol Donn, and (e) Drains.

Figure 5.11 shows linear modelled carbon dioxide fluxes by site using the climate data for 2004. Fluxes were modelled hourly from the 1st January 2004 to 13th December 2004. The lines in Figure 5.11 are lowess smoothed lines for the CO_2 fluxes for 2004 and account is now taken of daytime and night time fluxes over an entire year. Nam Breac (Figure 5.11 a) stands out as a site that is fixing less CO_2 and indications are that it may be a net source. In contrast the Drain site apparently fixes the greatest amount of CO_2. The other three sites appear to be similar in terms of CO_2 flux alone. Figure 5.12 shows the same information as Figure 5.11 but this time instead of the log linear model for CO2 in the light the non-rectangular hyperbola is used to model fluxes. There appears to be shift upwards in Figure 5.12 compared with Figure 5.11 indicating that the non-rectangular hyperbola estimates less carbon fixation in the light than the log linear model. However, the same patterns are reflected in terms of sites such that Nam Breac appears to be a source of CO_2 (although it is now a distinct source without sequestration) and the Drain site is still the largest sink for CO_2.

Figure 5.13 models the fluxes for the same period and uses the same climate data but here the influence of CH_4 is an added contribution. The data are modelled as the sum of CO_2 and CH_4 represented as CO_2 equivalents for three different scenarios 20, 100 and 500 years. This takes account of the greater Global Warming Potential (GWP) of CH_4 but also of its decreasing warming potential over time. On a mol/mol basis CH_4 has a 21.8, 7.6 and 2.6 times greater GWP than CO_2 over the 20, 100 and 500 time horizons respectively (Whiting & Chanton, 2001). Unfortunately no CH_4 relationship for the Drain site could be determined; therefore, this site is omitted from Figure 5.13.

For Nam Breac and Leir adding the CH_4 seems to make little impact to the carbon balance with Nam Breac remaining a source in all three scenarios and Leir remaining a sink (Figure 5.13a and 5.13c). However, for both Sletill and Maol Donn the influence is more marked with both sites sources over the 20-yr scenario. Maol Donn also is a clear source at 100-yr but for Sletill it is less clear perhaps being neutral over this scenario. However, both sites become sinks when considered over the 500-yr scenario. In Figure 5.14 the same information is presented as in Figure 5.13 except the non rectangular hyperbola is used to model the light fluxes. Here again there is an upward shift towards more positive fluxes although comparisons between sites remain the same as Figure 5.13. Now most sites though, except perhaps Leir, would be considered sources of carbon over the three CH_4 scenarios.

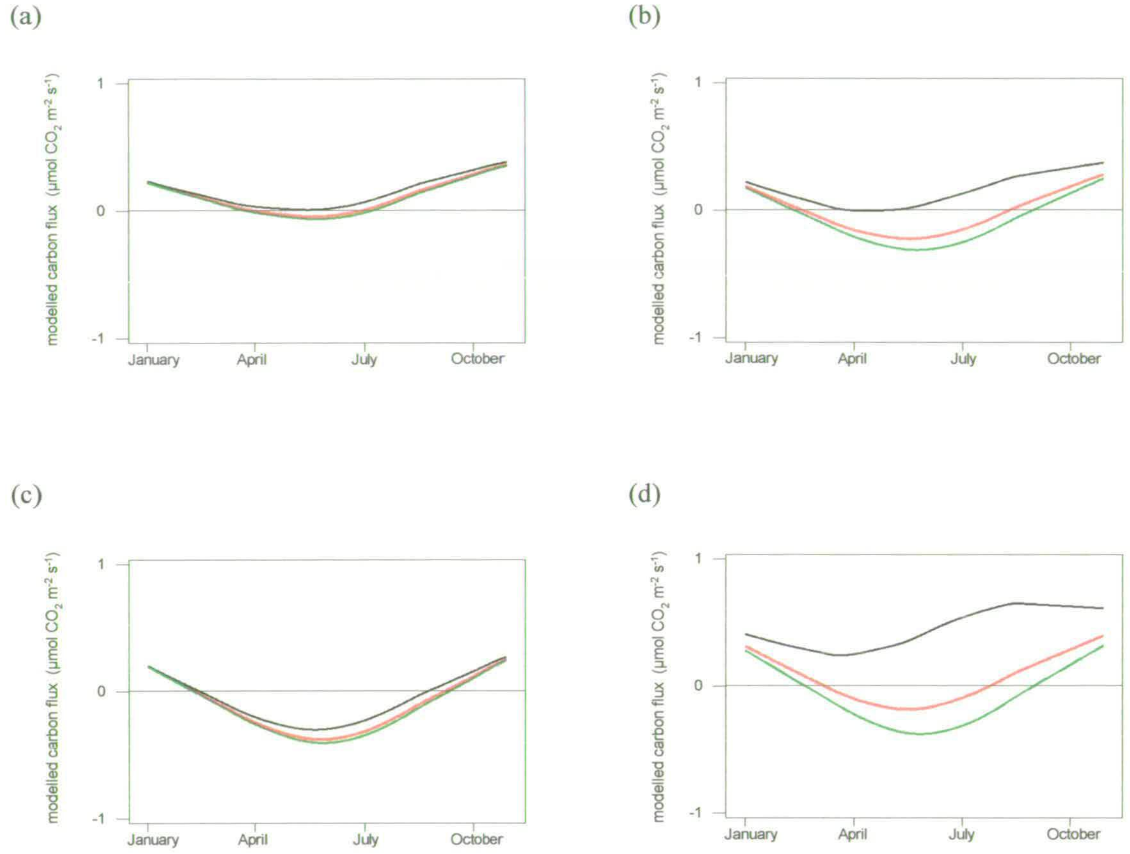

Figure 5.13: Modelled sum of carbon dioxide and methane fluxes (μmol CO_2 m^{-2} s^{-1}) for Forsinard sites, except Drain site, using linear regression equations in Table 4.3 and climate data from Kinbrace Meteorological Station 2004. The modelled sum of the fluxes takes account of the changing Global Warming Potential of CH_4 for 20-yr (black line), 100-yr (red line) and 500-yr (green line) time horizons. Lines are lowess smoothers with 0.5 degree of smoothing and 2 steps. Modelled flux for; (a) Nam Breac, (b) Sletill, (c) Leir, and (d) Maol Donn.

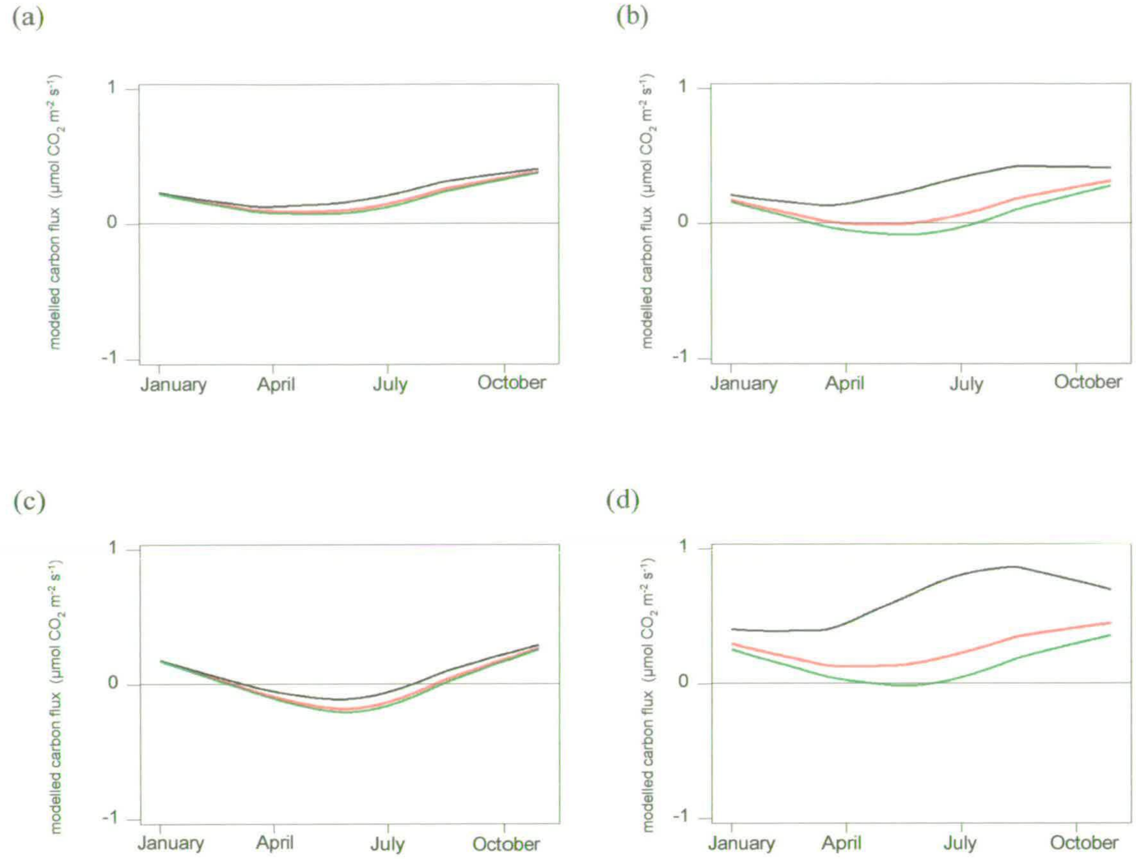

Figure 5.14: Modelled sum of carbon dioxide and methane fluxes (μmol CO_2 m^{-2} s^{-1}) for Forsinard sites, except Drain site, using non rectangular hyperbola and linear regression equations in Table 4.3 and climate data from Kinbrace Meteorological Station 2004. The modelled sum of the fluxes takes account of the changing Global Warming Potential of CH_4 for 20-yr (black line), 100-yr (red line) and 500-yr (green line) time horizons. Lines are lowess smoothers with 0.5 degree of smoothing and 2 steps. Modelled flux for; (a) Nam Breac, (b) Sletill, (c) Leir, and (d) Maol Donn.

5.5 Discussion

5.5.1a Statistical analyses using GLM

The unbalanced nature of the data analysed and multiple tests from the GLMs mean that the p values in Table 5.2 can only be considered approximate. Nonetheless the results indicate that there are significant effects on gaseous fluxes either through site or site climate interaction effects. That these differences were detected in fluxes of CO_2 in the light and dark and CH_4 imply that management affects the carbon cycle processes of photosynthesis, soil respiration and methanogenesis. That different kinds of effects were detected in the main sites during 2003-4 compared to 2005, is partly due to the fact that the 2003-4 data has modeled climate variables in the CO_2 light analysis. However that site effect was detected in 2003-4 and site soil temperature interaction were detected in CO_2 dark fluxes may be due to the differing seasons the datasets span. It may be that when winter is taken into consideration site effects are more apparent but when only summer and autumn data are analyzed the site soil temperature interaction is evident. This not only highlights the dynamic nature of CO_2 fluxes but also that seasonal variation is an important factor in dataset evaluation.

Due to the small sample size in the fire sites the evidence for effects presented here is weak. The lack of CO_2 light site or site and climate interactions at the fire site may be due to the use of modeled climate data. Although, the evidence points to a site effect on CH_4 flux and the burnt site appears to emit more CH_4, the question remains whether this effect can be attributed to fire. It is possible that the fire leads to increased CH_4 flux through an increased availability of nutrients for microbial methanogenesis from ash deposition (Hogg et al., 1992). There is evidence of increased microbial numbers after burning (Maltby & Edwards 1984, cited in Tucker 2003) but it is also possible that shifts in microbial community composition may lead to less methanotrophy perhaps leading to an apparent increase in methanogenesis. As there is a still a lack of research into the effects of fire on peatland microbial communities (Tucker, 2003) this speculative, also the comparison here is between one burnt area and one unburnt area and the result may be anomalous.

The evidence for the effects of a soil temperature drainage interaction also need to be treated with caution as no linear or exponential relationship between soil temperature and CH_4 fluxes could be determined in Chapter 4 and also there was marked heterogeneity of variance. Mean water table levels at the drain site suggest that differences in water table may be more to do with subsidence of the peat than alteration due to increased run off. Since these drains may be more than 30 years old disruption to carbon cycle processes may have had time to equilibrate. Effects are likely to be more apparent in the immediate period after drains are cut and much other work indicates this is the case (Cannell et al., 1993; Anderson et al., 2000; Minkkinen et al., 2002).

Although the effect of management of vegetation and primary productivity has been addressed in the UK (Grant et al., 1985; Shaw et al., 1996), there are few studies addressing the effect of management on carbon dynamics. Peat core work at Moor House in northern England detected differences in carbon accumulation between burning treatments but not grazing treatments (Garnett et al., 2000) reduced peat accumulation due to fire has also been observed in Canada (Kuhry, 1994). With such limited evidence and because this study is from one area of Scotland, it is questionable as to how representative these results are for UK blanket bog. In a recent review of carbon stocks and trace gas fluxes of EU peatlands all managed and natural ombrotrophic bogs were considered to be net sources of carbon except for those given over to Forestry –105 kg ha^{-1} yr^{-1} or 0.007 μmol CO_2 m^{-2} yr^{-1} (Byrne et al., 2004). These Forestry figures need to be considered with caution though because of the time difference to reach carbon equilibrium between Forestry (100 yrs) and bog (1000s yrs). However, figures of net sources from the managed bogs considered (such as drained bogs) were almost an order of magnitude above those of the natural bog (192 kg C ha^{-1} yr^{-1}) (drained bog 1253 kg C ha^{-1} yr^{-1}) and restored bog was the second lowest source at 736 kg C ha^{-1} yr^{-1} (Byrne et al., 2004). This evidence would appear to indicate that management practices affect carbon balances and thus the results presented here are indicative. However there is still a great deal of variability and the range of values within bog types reviewed by Byrne et al., (2004) often span 1 or even 2 orders of magnitude. Further investigation into the effects of management on carbon fluxes would seem warranted.

5.5.1b Graphical exploration of Main Sites and Sites L, M and N

In comparing the data for the mains sites and sites L, M, and N, although the climate variables and gaseous fluxes on these days appear to be related, there are still some discrepancies observed in Figures 5.1 to 5.4. This may be partly due to use of a remote weather station rather than data from sites. However, even when fluxes are complementary to climate variables there is also a correspondence with management. For example, CO_2 flux in the dark at Sites L, M, N and Nam Breac appear to be consistently higher rate of loss of carbon dioxide but is not always matched by corresponding soil temperature. These sites have more bare peat than the other sites therefore it is possible that this may be related to site management as these sites also have higher numbers of deer footprints than other sites (see Chapter 3) thus having a consequence on respiration rates. However, these do only represent one day of sampling at each of the sites and one must not draw too many conclusions from this data.

5.5.2 Relationship of vegetation to water table penetrometer data and gas flux responses slopes

The results of the ordination shown in Figures 5.5 and 5.6 offer some evidence for differences between gas flux plots. There appears to be some clustering of plots from the same site therefore perhaps some differences between sites in terms of the gaseous flux responses to climate variables. However small sample size is an issue here and the results are non-significant. However there is also evidence in the literature for these differences, for example, the relationship with water table and methane flux response slope is well documented (Martikainen et al., 1992; Bubier & Moore, 1994; Bubier, 1995; Bubier et al., 1995; Bergman et al., 1998; Hargreaves & Fowler, 1998; MacDonald et al., 1998; Bergman et al., 1999; Hughes et al., 1999; Kettunen et al., 1999) (see Chapter 4 also). That lower penetrometer readings are also associated with higher CH_4 slope is because both lower penetrometer readings and high methane flux are associated with Maol Donn. This may perhaps suggest that the combination of water table and peat compression may be indicators of higher CH_4 flux. That some species are correlated with particular regression slopes such as bare peat (low CO_2 – PAR response) *Sphagnum magellanicum* (high CH_4 - soil temperature response) and *Sphagnum capillifolium* (CO_2 – PAR response) and *Myrica gale* (CO_2 dark - soil temperature response) may be evidence of indicators of carbon dynamics. Although the results of the ordination are not significant, the small sample size here may suggest their value as indicators is worthy of investigation.

5.5.3 Tentative carbon balances

The strong relationships between climatic variables and site fluxes and the significant relationships found in the GLM analysis indicate that the calculation of site fluxes over one year (2004) would appear reasonable. The models indicate that large differences are evident between sites if the predicted relationships hold. What the response curves and regression model findings do indicate though are workable models upon which further work and more intensive and wide-ranging sampling are likely to yield further insight. Although the purpose of these models is exploratory and one must not lend a great deal of weight to these findings, it is interesting to examine how realistic these models are.

Firstly how representative of the 'general' climate is 2004? Table 5.3 shows UK Meteorological data for each month in 2004 for the North of Scotland area, which covers the Forsinard area. In terms of this study temperature and light were used as predictors, therefore, temperature and duration of sunshine are the important features of Table 5.3. From Table 5.3 it can be seen that all months were warmer than the 1961-1990 long-term average other than October, which was slightly colder. Comparison of the duration of sunshine with the long-term average was more variable, three months exhibit a distinctly greater duration; March, August September; with February, May and December showing a marginally greater duration. Three months clearly show less sunshine: April, June and October; and January, July and November have a slightly less duration. In terms of biological activity the months April to October are the most important since it is between these months that temperatures and light levels are sufficient to allow processes such as respiration and photosynthesis to take place. The consequence of warmer temperatures in 2004 may mean that modelled CO_2 flux respiration in the dark is overestimated by the model than if the model were that based on temperatures of 1961-1990 long-term average. Warmer temperatures for 2004 may also mean an extended growing season since temperatures are above the threshold 5 ^{o}C used here for CO_2 flux due to photosynthesis. The modelled CO_2 flux in the light here though is primarily driven by PAR. The fact then that the 2004 summer months have slightly less sunshine than the 1961-1991 average, may mean the extended season is mitigated by slightly lower light levels. This may have lead to a modelled photosynthetic activity that is not dissimilar to the 1961-1991 long-term average.

At present there is no information on the extent of management practices on the Forsinard Reserve. It is therefore difficult to gauge how representative the sites modelled here are in terms of management of the Forsinard reserve as a whole. In terms of vegetation the NVC communities M17 (especially in the east of the reserve) and M18 (in the west) appear to be the two most common communities (Russell et al., 2004) and these are apparent as sampled site communities, particularly M17 (see Table 5.1). However as shown by the evidence above in terms of vegetation and structure the NVC does not appear to be particularly sensitive, differences exist when sites are shown to be the same community (Chapter 3). The removal of the drain site in for the modelled fluxes of Figure 5.12, as no CH_4 climate relationship was ascertained, is unfortunate since it reduces the sites from five to four and thus the management treatments portrayed. This makes evaluation of the models on a Forsinard basis less representative as there are significant areas of the Forsinard reserve that have been subjected to drainage. Thus the evidence should be treated with caution.

Table 5.3: Maximum, minimum and mean monthly temperature, hours of sunshine and rainfall for the North of Scotland for 2004 (source: UK Meteorological Office). The column headed 'Actual' represent recorded values for that month, the column headed 'Anom' (anomaly) shows the difference from or percent of the 1961-90 long term average.

	Max temp		Min temp		Mean temp		Sunshine		Rainfall	
Month	Actual (°C)	Anom (°C)	Actual (°C)	Anom (°C)	Actual (°C)	Anom (°C)	Actual (hrs)	Anom (%)	Actual (mm)	Anom (%)
Jan	6.9	1.5	1.7	1.5	4.3	1.5	41.6	91.0	130.5	145.0
Feb	6.0	1.4	-0.5	0.3	2.8	0.9	63.3	101.0	152.3	130.0
Mar	8.0	1.7	1.4	1.1	4.7	1.3	112.4	126.0	106.5	73.0
Apr	10.3	1.6	4.1	2.5	7.2	2.0	97.2	74.0	130.5	147.0
May	13.4	1.5	5.5	1.2	9.3	1.3	168.5	106.0	66.7	76.0
June	14.6	0.2	8.3	1.3	11.4	0.7	99.3	66.0	134.8	147.0
July	15.8	0.4	9.0	0.3	12.4	0.4	121.1	96.0	78.0	78.0
Aug	17.4	2.0	10.6	2.0	14.0	2.0	153.2	124.0	157.7	131.0
Sept	14.6	1.4	7.9	0.8	11.2	1.1	117.9	130.0	212.1	136.0
Oct	10.0	-0.6	4.7	-0.3	7.4	-0.4	49.6	73.0	199.1	113.0
Nov	8.3	1.6	3.2	1.7	5.8	1.7	34.4	90.0	163.9	90.0
Dec	7.4	2.1	1.7	1.5	4.5	1.8	23.1	102.0	248.5	140.0

Although modelled site 'behaviour' appears consistent, using different mathematical models can lead to very different conclusions. A mean value for carbon fluxes for Forsinard in CO_2 equivalents for the 100-year scenario gives a carbon sink of -0.128 μmol CO_2 m^{-2} s^{-1} using linear models. Including the non-rectangular hyperbola gives a mean value of 0.047 μmol CO_2 m^{-2} s^{-1} turning from a sink to a source. This may in part be due to the fact that there are fewer data points in high illumination therefore A_{max} may be underestimated (see chapter 4) leading to an underestimation of flux in the light. Also the log linear models appear to have a steeper initial slope than the non-rectangular hyperbola (Figure 5.7 and 5.8) which would suggest a quicker attainment of net negative fixation rates.

Including an exponential model for CO_2 fluxes in the dark halves the linear model value to -0.061 μmol CO_2 m^{-2} s^{-1} for the 100-year scenario and would increase the overall source effect if both exponential and non-rectangular hyperbola were used. Including an exponential model for CH_4 though makes little difference giving a mean value of -0.118 μmol CO_2 m^{-2} s^{-1} carbon sink using a linear model for CO_2 flux in the light for the 100-year scenario.

Given the above caveats, the mean modelled carbon flux using linear models and the 100-year scenario for Forsinard translates to a carbon sink of -0.128 μmol CO_2 m^{-2} s^{-1} which equates to -48 g C m^{-2} yr^{-1} the mean for the non-rectangular hyperbola translates to a source of 0.047 μmol CO_2 m^{-2} s^{-1} or 18 g C m^{-2} yr^{-1}. Assuming this is a reliable estimate of the mean gaseous carbon flux for the Forsinard area this would be between an estimated sink of –0.48 t C ha^{-1} yr^{-1} and a source of 0.18 t C ha^{-1} yr^{-1} for the Forsinard Reserve. If we assume a loss due to water transport of approximately 103 kg C ha^{-1} yr^{-1} as reported for the river Halladale (Hope et al., 1997) this translates to either a sink of –0.38 t C ha^{-1} yr^{-1} or a source of 0.28 t C ha^{-1} yr^{-1} depending on the model used. However this takes no account of losses due to fire and without data on fire frequency this is difficult to incorporate. Peat accumulation rates for blanket bog in the UK vary between 0.1 and 1.2 mm yr-1 (Tallis, 1995). Approximating the peat carbon content as 0.47 kg C m^{-2} cm^{-1} depth (Cannell et al., 1993), these accumulation rates would then approximate to carbon fixation rates between –0.047 t C ha^{-1} yr^{-1}or -0.564 t C ha^{-1} yr^{-1}. The linear models generated a figure of –0.38 t C ha^{-1} yr^{-1}, which lies at the top end of these accumulation rates. Given that the modal peat accumulation rate stated by Tallis (1995) is approximately 0.2 mm yr^{-1}, the linear modelled values would thus seem to overestimate realistic UK fluxes. Published greenhouse gas balances for undisturbed European ombrotrophic peatlands range from –0.078 t C ha^{-1} yr^{-1} to 1.459 t C ha^{-1} yr^{-1} (Byrne et al., 2004). The linear modelled value far exceeds the lower estimate it therefore still seems reasonable to assume that the linear model represents an overestimate. When modelling fluxes using the non-rectangular hyperbola the resulting model estimate lies within the European ranges and may appear to be more realistic. Nevertheless there are many assumptions associated with the above calculations and the model for carbon balance does over simplify complex biological processes. The value of using these simple regression responses to model the data is that it allows site flux calculations to be extrapolated over a greater time period than the field work allowed using the standard values for PAR and temperature for each site thus aiding the interpretation of the statistical differences found in the GLM, though final carbon balances values cannot be regarded as reliable.

5.5.4 UK Climate Change Scenarios

From the evidence above and Chapter 4 it is apparent that climatic variables are important drivers of gaseous carbon fluxes in peatlands. It is therefore pertinent to ask what the above evidence means in terms of predicted UK climate change scenarios for Forsinard peatlands. The UKCIP02 report predicts annual and seasonal changes in temperature and precipitation up till 2080 (Hulme et al., 2002). In the case of ecosystem responses to climate change the mean annual changes are of less interest than, for example, how seasonal changes affect the growing season. UKCIP02 predicted seasonal changes in temperature and rainfall for the north of Scotland using low and high emission scenarios for the year 2080 are given in Table 5.4. Given that temperature is set to rise between 1 and 3.5 °C by 2080 depending on the scenario, and that gaseous fluxes have been shown here to be partly temperature dependant, this would increase respiration using a linear model by 0.109 µmol CO_2 m^{-2} s^{-1} °C^{-1} and methane flux by 0.0018 µmol CH_4 m^{-2} s^{-1} °C^{-1}. From examination of Figure 5.11 it seems that CH_4 emissions may be particularly important in autumn and an increase in temperature in this period may exacerbate CH_4 fluxes. However simple temperature flux dependant relationships are not indicative of the complex processes that are involved. Temperature has different effects on enzymes and isozymes and other important factors include substrate (reaction) availability, and water and nutrient availability (Davidson & Janssens, 2006). In terms of CO_2 fixation the primary driver is light, although this is also partly temperature dependant and longer warmer summers are likely to increase the length of the growing season. The may also be some increase photosynthesis due to increasing CO_2 in the atmosphere but the overall effects may be, transient (Oechel et al., 1994) complicated by nutrient availability and temperature (Saarnio et al., 1998) and at the ecosystem level are unclear (Hulme, 2005). Global dimming (Wild et al., 2005) may also have some effect on photosynthesis through attenuation of the light available for photosynthesis (Stanhill & Cohen, 2001). This may lessen over time as particulates in the atmosphere are cleared but may also not have as much effect in areas of low population (Stanhill & Cohen, 2001; Alpert et al., 2005; Wild et al., 2005) and photosynthesis is limited by more than light levels, e.g. nutrient availabilities. Nonetheless, increased respiration rates may be somewhat offset by increased photosynthesis. The predicted rainfall figures are perhaps of most concern and although the trend seems to be for increased rainfall in winter and spring between 10 and 20% less rainfall in summer in conjunction with higher temperatures may prolong the desiccation periods for bryophytes and lead to shifts in vegetation composition from bryophyte dominated peatlands to those more dominated by vascular plants. Changes in vegetation due to climatic effects may be compounded by the actions of management but the unknown geographical status and intensity of present management practices on peatlands in the UK (see Chapter 1) would make these interactions difficult to predict. The decrease in rainfall over the summer period combined with higher temperatures is likely to lower water tables over this period thereby decreasing CH_4 emissions. However, increased rainfall in the autumn may raise water tables this together with a rise in temperature may see an autumnal pulse in CH_4 emission. An increase in fluctuation of water tables may however have consequences akin to drainage which also increases water table fluctuation (Stewart & Lance, 1991). This may result in a completely altered CH_4 production process the long-term consequences of which are unknown. The lowering of the water table may also increase fluxes of CO_2 through peat decomposition (Davidson & Janssens, 2006) if this is then coupled to a temperature rise there may be a positive interaction but due to the complex processes involved and the lack of consensus of how temperature affects decomposition relationships (Davidson & Janssens, 2006) the outcomes of this are difficult to predict.

Table 5.4: Predicted seasonal changes in temperature and rainfall by 2080 using UKCIP02 high and low emission scenarios with respect to model-simulated 1961-1990 climate (Hulme et al., 2002).

Season	temperature (°C)		rainfall (%)	
	low	high	low	high
winter	1 to 1.5	2 to 2.5	10 to 15	20 to 25
spring	1 to 1.5	2 to 2.5	0 to 10	0 to 10
summer	1 to 1.5	2 to 2.5	- 10 to -20	-20 to -30
autumn	1.5 to 2	3 to 3.5	within natural variability	0 to 10

5.6 Conclusions

- Statistically significant effects of management as indicated by site and site climate interactions were detected in relation to gaseous fluxes of CO_2 and CH_4. These indicate that damaged sites fix less and respire more CO_2 and the use of fire may lead to at least an initial increase of CH_4. However, the effects of drainage at Forsinard are difficult to assess.
- This appears to support the evidence of other studies demonstrating that management affects carbon fluxes through effects on vegetation, hydrology and peat characteristics, however there is still a great deal of variability.
- There are some characteristics associated with site and carbon flux response slopes that may be indicators of carbon fluxes such as water table peat compression and species composition. However, further elucidation of some of these requires additional research.
- The responses for fluxes of CO_2 and light and temperature and CH_4 and temperature provide a workable model for predicting net gaseous carbon budgets over the period of a year. Further work and more intensive and wide-ranging sampling would be likely to yield further insight using this approach.
- Given the temperature dependence of flux processes the UK scenarios for climate change are likely to result in greater fluxes. However changes in vegetation and water table are likely to result from changes in rainfall and be

further influenced by changes in management. The present uncertainty over geographical distribution and intensity of management practices mean that effects at Scotland or UK scale will be difficult to predict.

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Chapter 6: Discussion

This chapter brings together the evidence from preceding chapters and discusses the evidence for a management effect of on the gaseous carbon fluxes in peatlands. However it is necessary first to offer a critique of the chamber flux methodology in order evaluate any effects.

6.1 Critique of Flux Chamber Methodology

The choice of equipment for any ecological investigation is crucial and is usually made on theoretical, practical and economic grounds. For the measurement of gaseous fluxes two main techniques are available eddy covariance (also known as eddy correlation and eddy fluctuation) or chambers, either dynamic (steady state) or static (non-steady state). The decision to use static chambers in this study was made firstly on the grounds of the spatial definition that chambers offer that is not available with eddy covariance. This was fundamental if links between gaseous flux measurement, vegetation and management were to be made. Static chambers are also considered to be more effective than dynamic chambers at detecting low fluxes such as occur in winter (Livingston & Hutchinson, 1995). On more practical and economic grounds, static chambers are easier to transport and more economically viable as no gas flow equipment is required to keep the concentration of the gas of interest at steady state.

6.1.1 Chamber Critique: Theoretical Considerations

Firstly there are certain theoretical aspects of chamber flux measurements that require some elucidation, this not only allows an understanding of the processes involved, but may indicate which processes the chamber method can affect.

Transport of gases in the atmosphere is dominated by pressure and density-driven advection (horizontally) and eddy turbulence (vertically) but closer to the surface the influence of molecular processes increase (Oke, 1992; Livingston & Hutchinson, 1995). The surface exchange may be modelled as:

$$f = f_m + f_d$$

Where: f = net flux,

f_m = mass flow according to Darcy's law, and f_d = molecular flow according to Fick's law.

Darcy's law is defined as:

$$f_m = \frac{\underline{k\,C\,\rho}}{\eta}\, dP/dz$$

Where: k is the intrinsic air permeability of the soil,

C is the volumetric concentration,

ρ is the density of the gas of interest,

η is the viscosity of the gas of interest,

and dP/dz is the pressure gradient.

Diffusion, described by Fick's law is:

$$f_d = - D_o dC/dz$$

Where: D_o is the binary molecular diffusion coefficient,

C is the concentration of the gas of interest,

and z is distance.

Diffusivity is dependent on the gas itself and the substance through which it diffuses and varies approximately as the square of absolute temperature and inversely with total air pressure (Livingston & Hutchinson, 1995).

In soils of low permeability such as water logged peat, molecular diffusion dominates gas transport, diffusivity in water is about 10^4 times less than in air (Livingston & Hutchinson, 1995). Vegetation influences the gas exchange through production, consumption and transport. Transport of gases in the canopy is the result of turbulent mixing, migration across leaf is by molecular diffusion or mass flow governed by conduction via stomata and cuticle (Jarvis & McNaughton, 1986; Oke, 1992; Livingston & Hutchinson, 1995). In *Sphagnum* dominated peatlands it is likely to be molecular diffusion rather than mass flow that predominates, but there will also be the influence of species of Cyperaceae Poaceae and Ericaceae which are likely to be spatially variable. Static chambers operate by restricting the volume of air for exchange across the covered surface and net emission or uptake, measured as a change in concentration, is a good reflection of the trace gas exchange rate only if the chamber does not significantly perturb the gaseous production, consumption and transport processes involved (Livingston & Hutchinson, 1995). There are several factors associated with the methodology adopted in this study, which have the potential to disrupt these processes, these include:

- Chamber design.
- Alteration of ambient conditions when chamber closes.
- Disturbance associated with base insertion.

6.1.2 Chamber Critique: Chamber Design and Alteration of Ambient Conditions

The chamber design used in this study was a static or non-steady state without vent to the atmosphere and an internal fan. Some authors recommend the use of a vented chamber (Livingston & Hutchinson, 1995; Davidson et al., 2002) this is because vented systems are thought to reduce changes in pressure between inside and outside the chamber. Internal and external pressure was not recorded during the field work therefore this may be a source of error. However a vent may not be essential and through a venturi effect may also contribute to error (Conen & Smith, 1998) this effect is likely to be more prevalent in windier areas such as the north of Scotland. However the presence of venturi effect in not considered unequivocal (Davidson et al., 2002) and the omission of a vent may lead to problems. Examination of Darcy's and Fick's Laws above would indicate that this is more of a problem where mass flow dominates the net flux. Molecular diffusion is likely to the more important process in terms of soil fluxes in water logged peatlands therefore differences in pressure may have less of an effect. Pressure effects may be more serious when vegetation is included, however, vascular plants are less dominant in peatlands and it may be that differences in pressure are less important. It is also likely that differences in pressure are relatively small compared to the effect on fluxes of, for example, differences in habitat due to management. However in the absence of data regarding the pressure inside and out of the chamber during measurements this is speculative and therefore, differences in pressure remains an unknown but potential source of error.

A mixing fan was included within the chamber, these fans have been connected with altering flux rates in comparison to systems without fans (Le Dantec et al., 1999) however, the consistent use of a fan for all flux measurements would seen to preclude this effect.

The time a chamber is enclosed is especially important since the longer the period the more chance there is of altering chamber conditions relative to ambient, changes in temperature especially need to be kept to a minimum since biological process respond to changes in temperature. In the light, the use of Propafilm C© helps to reduce this as has this substance has a high thermal transmittance (Hunt, 2003) also, keeping chamber closure to a maximum of 5 minutes for CO_2 ensured that differences between ambient and chamber were kept to a minimum. Further this was only likely to be a problem in the summer, in high light conditions, and as this is when flux rates are at their greatest this allowed shorter closure periods. However, temperatures within the chamber were usually slightly higher than ambient conditions but changes within the chamber were mirrored by changes in ambient temperature suggesting concurrent responses. Relative humidity was also usually greater within the chamber but as relative humidity was only weakly associated with fluxes (Chapter 4 and 5) this may be less important. Also recorded light, temperature and relative humidity inside the chamber were all within a ‘natural range’ and the use of climate variables as co-variables in statistical analysis offsets their effect on any testing differences between sites. Flux responses in the dark chamber (used for CO_2 and CH_4) are less related to air temperature and humidity and more to soil temperature. No effect on soil temperature was noted even over the longer period when CH_4 measurements were made.

The increasing concentration of gas in the headspace according to Fick’s law the ground must affect molecular flow as the flow is dependent on the concentration of the gas in question, therefore it is possible that this static method underestimates fluxes (Davidson et al., 2002). A serious lessening of the flux would have presented itself as a curve rather than a linear representation in the data. Graphical examination of the data and rejection criteria based on an R^2 adjusted value of 0.9 would help to detect and preclude this. Keeping the chamber closure time to 5 minutes or less for CO_2 would also help to minimise this effect. It is more difficult to asses this affect for CH_4 as only four samples were taken and closure times were up to 30 minutes but concentration of this gas are much smaller and the same rejection criteria was employed. Also the soil diffusivity in wet peat is lower than other more porous soils and the volume to area ratio of the chambers used here is large so the effect may be lessened (Davidson et al., 2002). Chamber volume to area ratio must be large enough to exhibit a constant rate of concentration change but not so large as to have excessive enclosure periods (Livingston & Hutchinson, 1995). As both CO_2 and CH_4 measured there is trade of between optimal volume to area ratio. The volume to area ratio of 0.28 m allowed constant concentration changes and quick enough closure times not to affect conditions too much.

Another problem for this study related to volume is what may be termed the effective volume (Rayment, 2000). Rayment (2000) used this term to describe how static chambers for soil respiration consistently underestimate fluxes because the chamber includes soil pore spaces. This is not so much the problem in peatland sampling as pores are usually filled with water but the reverse effect may be present when vegetation is included in the chamber reducing effective volume (relative to being placed on a flat surface) and may be also exist due to the hummock-hollow nature of the habitat. This was partly addressed by measuring heights ($n = 4$) relative to the top of the base and the vegetation in estimating the volume of the base this was then added to the volume of the chamber top to give a unique volume every time a flux measurement was made. This would help to reduce discrepancies in effective volume due to the hummock-hollow nature. However, the only way to address the vegetation is to actively measure the biomass within the chamber. This is undesirable because of the destructive nature of biomass measurements. However assuming a building phase *Calluna* assuming a biomass of 2 kg m^{-2}, which is greater than biomass reported for bog *Calluna* (Forrest, 1971; Forrest & Smith, 1975), would give approximately 250 cm^3 of biomass within the chamber or 0.2 % of chamber volume. As noted in the section below the chamber was not deployed in building *Calluna*, therefore, we can assume vegetation portion of the chamber volume to be negligible.

6.1.3 Chamber Critique: Disturbance associated with base insertion

This is potentially the most serious source of error in the present study. In fact the physical insertion of the chamber base into the peatland habitat causes so much disturbance in certain vegetation, as to rule out the method from use. Figure 6.1 shows the before and after insertion of the base in a *Calluna* dominated bog. It is clear that to use this technique in this vegetation would be unreasonable, as the plot is in no way representative of the habitat after disturbance. In terms of representation of blanket bog vegetation covered by the present study this is a fairly serious omission since a large proportion of the bog in the UK particularly in the Southern Uplands and England and Wales have a high proportion of *Calluna* dominated bog. The disturbance effect arises due to the layering habit of *Calluna*. Tests with other base designs such as frames with weighted skirts did not work as an adequate seal between the skirt and the peat could not be achieved, the solution awaits further design and testing.

Figure 6.1: The effect of inserting chamber base into *Calluna* dominated bog. (a) before chamber insertion, (b) after chamber insertion.

The continual moving of chamber bases and walking around chambers to remove and replace chamber tops undoubtedly had an effect on the surrounding habitat. However vegetation within the plot tended to remain intact suggesting CO_2 fluxes in the light may not have been affected.

Out-gassing from the peat by chamber insertion was identified as a potential problem in a preliminary study in the Lammermuir Hills by increases in flux rate. This effect lessened over time, hence the 35 minute gap before measurements were taken, however it may still have been a potential problem with plots numbers 1 and 5 since time between insertion and measurement was less in these 2 plots because of the way plot sampling was structured. However, mean CH_4 flux for 2005 from 'disturbed' plots was 0.233 μmol CH_4 m^{-2} s^{-1} (SD 0.021, n = 114) compared to 0.229 μmol CH_4 m^{-2} s^{-1} (SD 0.025, n = 37) for those plots with a longer period before measurements suggests that this disturbance does not appear to affect fluxes greatly.

In addition to the out-gassing effect from peat, bubble release was also a potential source of error but only appears to have occurred at Maol Donn. Here it was possible to initiate a pulse of CH_4 (though apparently not CO_2) due to chamber closure disturbance. The reasons for this happening at Maol Donn are likely to be firstly because this site had higher emissions of CH_4 therefore, the concentration of CH_4 within the peat was likely to be higher and secondly the softer peat (see penetrometer readings in Chapter 3) associated with this site. These two factors allowed gas bubbles to be released when chambers were closed. Bubble release was also observed naturally at this site but was not observed at any other site. This type of problem was easily detected from graphical examination of CH_4 concentration against time. Once detected, the associated flux rate was either not included in any further analysis or flux rates were calculated from the 3 data points after the initial pulse. Particular attention was paid to whether these were linear and within the normal range for this site, data not linear or outwith this range were discarded.

6.1.4 Chamber Critique: Other Methodological Noise

Further sources of error may come from the gas chromatography (GC) methodology. Automatic sampling is the preferred method for GC measurement (Crill et al., 1995) this was not used here this and may have introduced some noise into the data. This is likely to be more of a problem when flux rates are small, such as in winter, therefore it may be that some of these fluxes may have been undetectable due to noise; coefficients of variation averaged 1.4 % for gas standards comparable to the precision of other hand injected GC studies (Crill et al., 1995).

Sampling CH_4 in vials has the potential for leaks to affect concentrations in the vial. Over-pressurisation of vials with chamber air made easy detection of leakage also a test on vials left for 6 months after being sampled with 10 ppm CH_4 showed only a slight loss of CH_4 (mean CH_4 concentration was 9.6 ppm, +/- 0.17 SE, n = 51), gas sample vials were left for a maximum of 2 weeks before analysis.

It is generally considered that chamber methods may under estimate flux rates (Davidson et al., 2002). As the emphasis in this study is placed more on the differences between sites rather than estimation of the 'true' flux rates, the chamber method was consistent between sites and therefore any under (or over) estimation is also likely to be consistent, although more replication would have been desirable.

In summary, although chamber methods have problems, most of these can be overcome with appropriate data assessment procedures and replication. Therefore, the chamber method as used here appears to represent not only a cost effective but one of the best ways of estimating gaseous fluxes in spatially defined areas.

6.2 Does Management Affect Carbon Fluxes?

Chapter 1 introduced the carbon cycle of peatlands and some hypotheses of how anthropogenic management may affect this cycle. Figure 6.2 re-introduces this cycle but with effects of management super imposed. Figure 6.2 proposes that directly or indirectly management can affect the carbon cycle of peatlands through the vegetation and acrotelm directly and then through consequent indirect effects. The question remains though, does this thesis offer evidence to support the existence of these illustrated effects or do they remain theoretical?

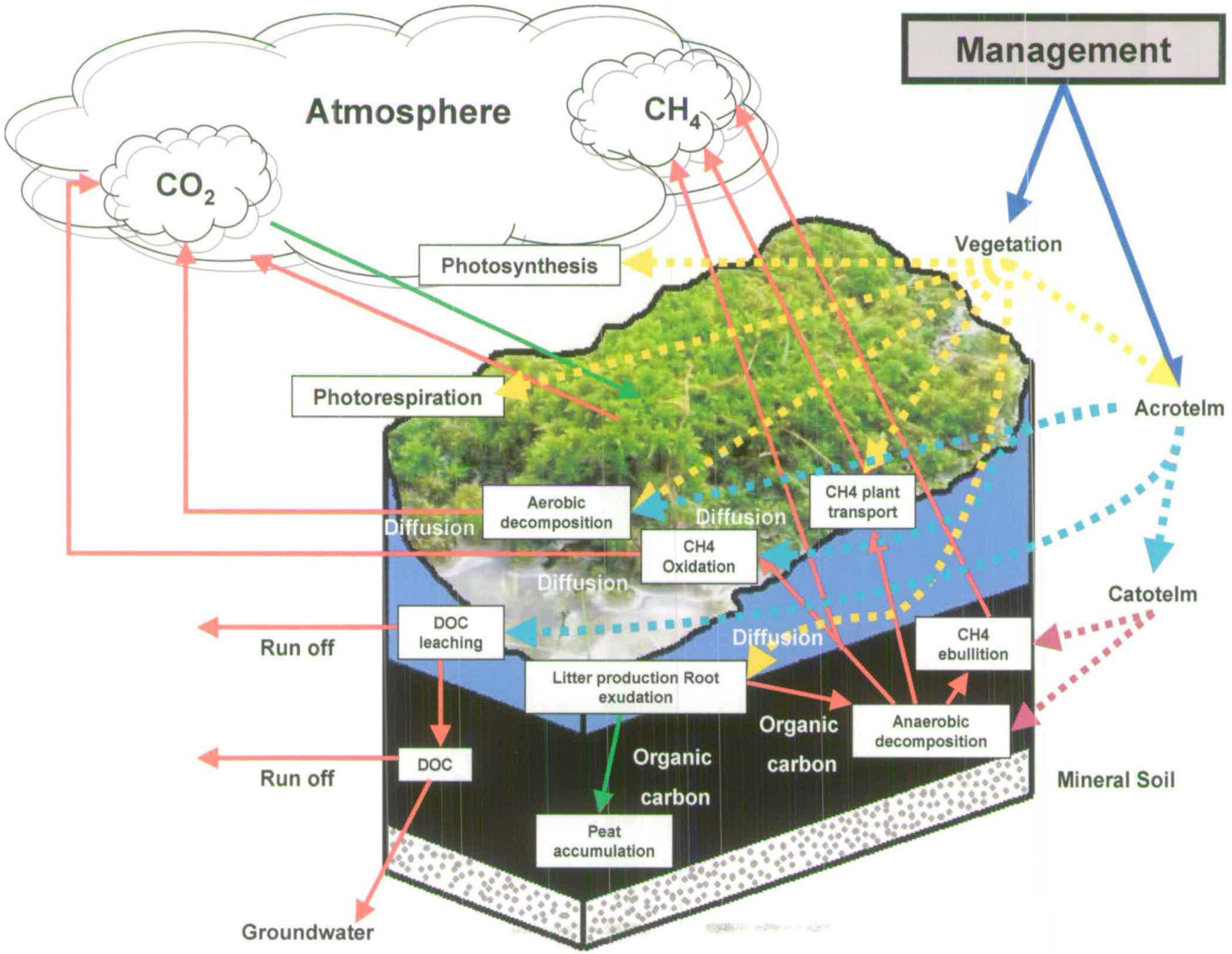

Figure 6.2: Schematic representation of the peatland carbon cycle with the influence of management superimposed. Solid red arrow = losses of carbon, solid green arrows = gains of carbon, solid blue = direct influence of management and dashed lines = indirect influence.

Chapters 1 and 2 reviewed the literature evidence for management effects on the blanket bog ecosystem. It is apparent that the hypothesis for management effects on the vegetation is supported by evidence in the literature. Chapter 3 presented new data to further support this vegetation effect hypothesis, not only in terms of species composition but also vegetation structure. Plants may affect gas exchange through alteration of the chemical and physical environment hosting micro-organisms, uptake and release of resources for microbial biomass, foliar exchange or as a direct pathway for flow such as aerenchymatous species (Clymo, 1984; Jarvis & McNaughton, 1986; Oke, 1992; Livingston & Hutchinson, 1995; Joabsson et al., 1999). Therefore disturbance of vegetation through management must disturb the gaseous exchange processes in some manner. Thus, it would seem that the link between this and carbon fluxes should be theoretically self evident. However, the present gaseous carbon flux literature from the UK reviewed in Chapter 2 is lacking in evidence for the direct effects of management on carbon fluxes except for forestry and forestry related drainage (Cannell et al., 1993; Cannell & Milne, 1995; Fowler et al., 1995; Anderson et al., 2000; Hargreaves et al., 2003) the effects of grazing and burning though appear to remain elusive. There is however evidence of this type of management affecting carbon balance of one site, Hard Hill where burning reduced carbon sequestration but grazing effects were not identified (Garnett et al., 2000). Evidence from outside the UK is more extensive and includes mainland Europe and Canada but the management practices examined are mainly either related to forestry (drainage) or peat extraction (Sakavets & Germanova, 1992; Martikainen et al., 1995; Komulainen et al., 1998; Nykanen et al., 1998; Komulainen et al., 1999; Sundh et al., 2000; Tuittila, 2000; Tuittila et al., 2000; Minkkinen et al., 2002; Tomassen et al., 2003; Glatzel et al., 2004; Marinier et al., 2004; Tuittila et al., 2004; Von Arnold et al., 2005). However even when management has been examined in terms of carbon fluxes the picture is not unequivocal and much variation is present (Byrne et al., 2004). Although forestry has been practiced on UK peatlands (though less practiced at present at least on deep peat) peat extraction is not common to blanket bog in the UK. Evidence for the effects of fire on carbon balance appear to also be lacking but may have serious implications and challenge the assumption that northern peatlands are a carbon sink (Turetsky et al., 2002).

Thus it would appear that one can make links to management affecting the vegetation and hypothesize about the effect on the carbon flux but the effect may not always be apparent as further research appears to be required.

Chapter 4 reinforced theoretical consideration for environmental controls on carbon fluxes. However, there appeared to be at least qualitatively different responses to environmental control at the site level. As Chapter 3 found differences in vegetation between sites at Forsinard that are considered to be indicative of management then this indicates an interactive effect of site and environmental controls on carbon fluxes.

These site differences and interactions were tested for in Chapter 5 and fluxes were simply modelled over the period of a year in an attempt to illustrate any differences. Significant interaction and site effects were detected using GLM's providing direct evidence of management affecting the gaseous carbon fluxes. The simple modelling approach appeared to make these differences more apparent suggesting that if year round measurements were made differences would be clear. However the models used are extremely simple and are unlikely to be indicative of complex biological processes. Nonetheless they offer support for the hypothesis that management affects gaseous carbon fluxes.

That climate changes is unequivocal, that climate will change in response to anthropogenic influences is becoming generally accepted. That important ecosystem carbon related processes, such as soil decomposition and photosynthesis, are affected by temperature, light, CO_2 concentration and water and nutrient availability is also unequivocal. Nevertheless we have no direct control over many of these factors and though the study of these relationships is undoubtedly important, it is apparent that only when coupled with the investigation of management practices is our ability to affect ecosystem carbon dynamics revealed. We have direct control over whether we light a fire or put one out, increase or decrease grazing numbers, drain or plough. Changing these actions spatially and temporally will affect carbon fluxes. Although these effects are likely to be dwarfed by changes in anthropogenic emissions, it is still important to conserve the large peatland carbon store. Peatland management affects the processes of decomposition and photosynthesis by the changing of vegetation and peat characteristics and the only way to assure the conservation of this carbon store is to combine the manipulation of habitats by management with the quantification of carbon fluxes.

In summary the evidence offered by this thesis supports the hypothesis that land management practices affect gaseous carbon fluxes. The implication of this in a UK and global context is that we can indirectly influence fluxes of carbon to the atmosphere by changing management practices that will have a feedback to atmospheric carbon concentrations.

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Chapter 7: Conclusions and Further Research

7.1 Conclusions

- The relationships between management practices and carbon flux of blanket bog ecosystems in the UK have been assessed revealing links between management, vegetation, and carbon fluxes, and highlighting gaps in knowledge and areas for further study.

- Blanket bog can be is defined as areas of semi-natural vegetation over-lying peat of at least 0.5 m depth and is the most extensive semi-natural land habitat in the UK. Peatland ecosystems represent a large carbon store and a distinctive assemblage of species, which, if lost, would decrease global biodiversity and potentially increase atmospheric carbon. Threats to peatland ecosystems include drainage, agricultural improvement, burning, the effects of large herbivores, peat extraction and climate change.

- The management practices of burning, grazing and drainage are known to affect peatland vegetation and therefore have either direct or indirect effects on peatland gaseous carbon fluxes.

- The restoration of blanket bog in the UK is a relatively recent phenomenon. Several procedures and policy options are available to landowners for blanket bog restoration. These include:
    - The Peatland Management Scheme
    - Scottish Forestry Grants Scheme
    - LIFE Nature (EU)
    - Heritage Lottery Funding
    - The Rural Stewardship Scheme (RSS)
    - Organic Farming (indirectly)
    - Land Management Contracts

- There is as yet no reliable estimate for the net gaseous flux rates of CO_2 from Scottish or UK blanket bog. Also the influence of management of gaseous carbon fluxes is lacking. There is a need for further research not only to address this but also to address the lack of spatial and temporal evidence. This has implications for UK climate change models, UK peatland ecosystem response to climate change and UK government policy. Derived estimates from continental peatlands are unlikely to be representative of UK conditions and further research is necessary to obtain useable estimates for the UK.

- Fluxes of methane from UK peatlands were reviewed from nineteen studies from 11 different sites all report emissions of methane, with an overall mean emission of 0.029 μmol CH_4 m^{-2} s^{-1}. However, only six of the nineteen explicitly state that winter measurements were included, and none of the studies record the management status of sites.

- Given the differences in methods, study durations and the size of the area of blanket bog to be covered, it is suggested that a meta-analytical approach to climate change research is adopted.

- Evidence from the Moor House Hard Hill experiment and Forsinard showed that between site vegetation composition pH, peat compaction, animal utilisation, and vegetation structure were different and the majority of these can be related to management.

- The NVC method is not indicative of site management at either Hard Hill of Forsinard. Therefore, the development of further methodology to assess the geographical spread and intensity of management of blanket bog in the UK is likely.

- However, that both Moor House and Forsinard are site-specific studies means that more research is required for the applicability of these studies to the UK situation.

- Relationships between gaseous fluxes and climate variables were identified. However, these did not always follow theory and departures may be related to site management.

- Statistically significant effects of management and interaction between management and climate were detected using general linear models on the gaseous fluxes of carbon dioxide and methane.

- There are some characteristics associated with site and flux responses to the environment that may be indicators of overall carbon balance such as water table peat compression and species composition. However, further elucidation of some of these requires research.

- The responses for fluxes of net CO_2 exchange and PAR and temperature and net CH_4 exchange and temperature, provide a workable model for predicting net gaseous carbon budgets over the period of a year. However these models are unlikely to encompass biological complexity.

- Given the temperature dependence of flux processes the UK scenarios for climate change are likely to result in greater fluxes. However changes in vegetation and water table are likely to result from changes in rainfall and be further influenced by changes in management. The present uncertainty over geographical distribution and intensity of management practices mean that effects at the Scotland or UK scale will be difficult to predict.

- Current and future models are likely to be ill informed in respect of the effects of management on the carbon balance of blanket bog habitat because management has not been considered in current gaseous carbon flux research.

- The evidence presented by this thesis indicates that management does affect carbon fluxes. Statistical analysis and modelling appear to show that damaged peatlands are sources of carbon, fire may increase fluxes of CH_4 (at least temporarily) and more intact sites appear to be sinks though this is dependent on the CH_4 scenario considered. This may indicate that the conservation of intact peatlands for biodiversity may lead to carbon gains or at the very least minimise carbon losses.

7.2 Further Research

As indicated above, there are several questions still requiring additional research including:

- What are the geographical extents of management practice on blanket bog habitat?
- Can the variability of management practices throughout the blanket bog habitat be quantified?
- Can the variability of fluxes of CO_2 and CH_4 in relation to management be quantified?
- Does management significantly affect fluxes to river systems?
- Do carbon fluxes from blanket peat catchments to river systems end up in the atmosphere and if so over what time scale?
- Do restored peatlands have a more positive or negative carbon balance than damaged peatlands?
- Can the carbon flux of blanket bog be characterised by using indicators of vegetation and management?
- Can the spatial variation in microbial communities be characterised in peatlands?

If an informed approach to policy regarding the dynamics of carbon from these peatland ecosystems is required, and estimates of how blanket bog ecosystems can adapt to climate change is needed, then further research is a prerequisite.

It is extremely unlikely that a definitive value for the carbon balance of the blanket peat resource can be measured; therefore, proxy approaches are required. The most commonly used method is to model fluxes mathematically, however this requires confidence in either the empirical data on which the models are based or upon the theories on which they are based. As stated above, current and future models are likely to be ill informed in respect of the effects of management on the carbon balance of blanket bog habitat because of the absence of the consideration of management in current gaseous carbon flux research.

One approach not yet considered may be to define and quantify easily identifiable and mappable indicators of carbon flux dynamics and management. Ellenberg indicator values (Hill et al., 1999) can be used in the characterisation of habitats from vegetation composition data. In Canada it has been noted that bryophytes are good indicators of methane flux as they reflect the long-term water table (Bubier & Moore, 1994). Aerenchymatous species can indicate increased methane flux (MacDonald et al., 1998; Joabsson et al., 1999), bare peat implies only respiration but no photosynthetic activity and erosion may be occurring therefore a loss of carbon.

There will be functional relationships between blanket bog species composition, carbon flux and management. Estimating productivity and decay rates for a range of the dominant blanket bog species may allow a carbon accumulation potential (CAP) to be determined that could then be scaled up to the landscape level from vegetation composition and structure data. The effects of grazing and burning on the spatial distribution and abundance of bog species could identify management options for the optimisation of carbon sequestration and biodiversity conservation. This kind of approach may allow a crude but effective way of estimating the implications of anthropogenic actions on the carbon dynamics of blanket bog in the UK. However, one possible source of existing information is the many papers concerning the production ecology of bogs and bog species, though this has not been addressed by the current review. Further, it may be possible to link in existing data from remote sensing as in the Scottish Blanket Bog Inventory (Quarmby et al., 1999; Johnson & Morris, 2000b, a, c, 2001)

The objective of the study would be to establish a carbon accumulation potential (CAP) value for the major peat forming species that could then be scaled up to the landscape level.

The suggested approach would be:

1. Develop indicator values for the dominant blanket bog species from studies for carbon dioxide fixation and loss in the laboratory, field and from the literature, to encompass the variety of climate conditions where blanket bog is found in the UK.
2. Develop indicators of water table, peat compression and nutrient status to that can indicate methane flux.
3. Combine indicators of carbon dioxide and methane into one indicator of CAP.
4. Develop a field methodology for assessing vegetation composition and structure to enable classification of polygons to CAP.
5. Botanical surveys using developed methodology
6. Prediction of CAP from surveys.
7. Flux research in the field relating to predicted CAP to gaseous flux measurements for calibration and comparison to predicted CAP.

This approach will not only allow for indications of carbon dynamics but as it is intimately linked to vegetation and management dynamics future changes can not only be predicted but re-sampling will allow explicit testing of prediction and further development of CAP.

7.3 References

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8. Appendices

These appendices are listed by the reference to each chapter but only Chapters 1, 2, 3 and 5 have a related appendix.

8.1 Chapter 1 Appendix

SI Units

In the course of the reviewing papers for chapters 1 and 2 it was noted that differing units that are sometimes not delimited by the chemical compound they relate to are used in published literature this leads to a few simple but important questions. Why are different units are reported and not bounded by chemical constituents? What typical assumptions are made when reporting fluxes? And are these problems serious?

For the standard reporting of results scientists are expected to use the appropriate SI unit for the species under study (BIPM, 1998). When reporting flux measurements it is usual to express the results in terms of the units of the substance measured, per unit area, per unit time. The SI unit for the standard of amount of substance is the mole (mol), the SI unit for length is the metre, therefore area is expressed as square metres (m^2) and the SI unit of time is the second (s). When expressing results in terms of a substance it is normal to explicitly state which substance has been measured e.g. CO_2 or C (this also follows for expression in units of mass). It therefore follows that the flux of carbon dioxide per unit area, per unit time, should be expressed as mol CO_2 m^{-2} s^{-1}. However, greenhouse gases are normally expressed in units of mass for the purposes of the U.K. Greenhouse Gas Inventory; the SI unit being kilogram (kg). Conversion of this means knowing the weight of 1 mole of carbon dioxide in 1 kg or more conveniently 1 gram (g). CH1 Appendix Table 1 below shows the conversion factors for this purpose.

In reality the amounts can be very small or very large and the measurements are reported as derivations of the SI base units, for example µmol CO_2 m^{-2} s^{-1}. The most commonly quoted multiplication factors are given in CH1 Appendix Table 2.

CH1 Appendix Table 1: Relationship between mole and mass in grams of chemical substances relevant to this thesis.

Chemical species	**grams**	**moles**
carbon C	1 mol = 12.01 g	1 g = 0.0833 mol
oxygen O	1 mol = 16.00 g	1 g = 0.0626 mol
hydrogen H	1 mol = 1 g	1 g = 1 mol
carbon dioxide CO_2	1 mol = 44.01 g	1 g = 0.0277 mol
methane CH_4	1 mol = 16.01 g	1 g = 0.0625 mol

CH1 Appendix Table 2: Prefixes and multiplication factors in common use.

Multiplication factor	**Abbreviation**	**Prefix**	**Symbol**
1,000,000,000,000,000	10^{15}	peta	P
1,000,000,000,000	10^{12}	tera	T
1,000,000,000	10^{9}	giga	G
1,000,000	10^{6}	mega	M
1,000	10^{3}	kilo	k
100	10^{2}	hecto	h
10	10^{1}	deca	da
0.1	10^{-1}	deci	d
0.01	10^{-2}	centi	c
0.001	10^{-3}	milli	m
0.000,001	10^{-6}	micro	μ

1 kilotonne (kt) = 10^3 tonnes = 1,000 tonnes

1 Mega tonne (Mt) = 10^6 tonnes = 1,000,000 tonnes

1 gigagram (Gg) = 1 kt 1 teragram (Tg) = 1 Mt

Attempting to answer why different units are used and specific chemistry is not explicitly reported would necessarily involve questioning the editors of the scientific journals where the results are reported and ask why there appears to be a problem. However, this is outwith the bounds of this thesis and more important are the assumptions made when deriving calculations and whether they influence interpretation. Here there need to be closer examination of how estimates are arrived at. The conversion between moles and mass will necessarily involve some rounding errors and small underestimation due to isotopic composition (e.g. naturally occurring oxygen is approx 99.759% O-16, 0.037% O-17 and 0.204% O-18) but these are unlikely to be serious. In trying to consider what further assumptions have been made in the calculation and whether or not these are important we must first consider how the measurements were collected. This involves examination of not only the method but also the number of samples and the period over which the study was conducted. There are usually no problems in using units of m^{-2} s^{-1} or m^{-2} hr^{-1} as most studied measure fluxes over comparable areas and longer periods than these; problems arise when units are expressed in terms of ha or km^{-2} or $month^{-1}$ or yr^{-1} as this usually involves extrapolation beyond the area or time period of the study.

For example, if CO_2 measurements were made by eddy-covariance at one blanket bog site for 2 days in June and 1 day in July we might reasonably expect the results to be reported in μmol CO_2 m^{-2} s^{-1} and with mean values for day and night. However, if a value for carbon sequestration is required for the whole of the UK blanket bog for submission to the UK Greenhouse Gas Inventory, and this is the only study available, it would be necessary to convert this figure to a mass value, extrapolate from the area reported in the study (ha) to the entire area of blanket bog in Scotland (1,927,000 ha), and extrapolate beyond the period of study (3 days in this case and not including winter) to arrive at a value in Gg CO_2 yr^{-1}. Without the information surrounding the study it would be easy to accept this value as being representative. Once given this information, however, one does not have much confidence in that value, although evaluation of the reported statistic and reflection on what improvements are necessary in order to acquire a more representative value is possible. One may think that this example is far removed from reality, however, these type of figures are exactly what are used for informing government policy. Chapman *et al.* (2001) report just such an extrapolative value for peat accumulation for the UK, although the authors acknowledge that their value is an extrapolation. This example is not used to offer undue criticism of these authors, indeed similar extrapolations are given in this thesis, merely to highlight the paucity of information that is available to arrive at reliable estimates for fluxes of carbon dioxide (or methane or fluxes to rivers) for blanket bog in the UK and emphasize the caveats associated with these type of figures.

Accordingly all results reported here including those from review papers and data collected for this thesis should be interpreted and/or used with caution.

CH1 Appendix Table 3: Carbon fluxes and concentrations in rivers in the UK from peatland catchments. Figures in brackets are 95% CI unless otherwise stated. * indicates information from a review article.

Reference	**Country**	**Site**	**DOC**	**POC**	**DIC**	**H CO$_3$ -C**	**Free CO$_2$**	**CH$_4$ - C**
Dawson *et al*., (2002)	Scotland	Brocky Burn	169 kg C ha^{-1} yr^{-1} (119)	18.5 kg C ha^{-1} yr^{-1} (17.9)	Not estimated	1.12 kg C ha^{-1} yr^{-1} (2.07)	2.62 (1.75) C kg C ha^{-1} yr^{-1}	< 0.01 kg C ha^{-1} yr^{-1}
	Wales	Upper Hafren	83.5 kg C ha^{-1} yr^{-1} (37.7)	27.4 kg C ha^{-1} yr^{-1} (19.0)	Not estimated	1.28 kg C ha^{-1} yr^{-1} (1.17)	8.75 (3.80) C kg C ha^{-1} yr^{-1}	< 0.01 kg C ha^{-1} yr^{-1}
Worrall *et al* ., (2003)	England	Trout Beck	9.4 g C m^{-2} yr^{-1}	19.9 g C m^{-2} yr^{-1}	5.9 g C m^{-2} yr^{-1}	Not estimated	3.8 g C m^{-2} yr^{-1}	Not estimated
Dawson *et al*., (2001b)	Scotland	Brocky Burn	8.13 mg l^{-1}	0.2-0.8 mg l^{-1}	Not estimated	Not estimated	1.71 mg l^{-1}	Not estimated
			6.87 mg l^{-1}	0.2-0.8 mg l^{-1}			1.34 mg l^{-1}	
			9.76 mg l^{-1}	0.2-0.8 mg l^{-1}			1.23 mg l^{-1}	
			21.3 mg l^{-1}	0.2-0.8 mg l^{-1}			1.61 mg l^{-1}	
			6.5 mg l^{-1}	0.2-0.8 mg l^{-1}			1.46 mg l^{-1}	
			7.05 mg l^{-1}	0.2-0.8 mg l^{-1}			1.46 mg l^{-1}	
			17.0 mg l^{-1}	0.2-0.8 mg l^{-1}			1.32 mg l^{-1}	
			12.7 mg l^{-1}	0.2-0.8 mg l^{-1}			1.03 mg l^{-1}	
	Scotland	Water of Dye	3.34 mg l^{-1}	0.2-0.8 mg l^{-1}			1.82 mg l^{-1}	
			3.28 mg l^{-1}	0.2-0.8 mg l^{-1}			1.35 mg l^{-1}	
			4.08 mg l^{-1}	0.2-0.8 mg l^{-1}			1.11 mg l^{-1}	
			16.0 mg l^{-1}	0.2-0.8 mg l^{-1}			1.77 mg l^{-1}	
			3.73 mg l^{-1}	0.2-0.8 mg l^{-1}			1.89 mg l^{-1}	
			3.54 mg l^{-1}	0.2-0.8 mg l^{-1}			1.35 mg l^{-1}	
			8.05 mg l^{-1}	0.2-0.8 mg l^{-1}			1.29 mg l^{-1}	
			9.90 mg l^{-1}	0.2-0.8 mg l^{-1}			1.26 mg l^{-1}	
Dawson *et al*., (2001a)	Scotland	Brocky Burn	2.62 mg l^{-1}	Not estimated	2.95 mg l^{-1}	Not estimated	Not estimated	Not estimated
			17.6 mg l^{-1}		1.79 mg l^{-1}			
			4.09 mg l^{-1}		1.19 mg l^{-1}			
			28.9 mg l^{-1}		0.55 mg l^{-1}			
			10.3 mg l^{-1}		1.67 mg l^{-1}			
			20.7 mg l^{-1}		0.95 mg l^{-1}			
			4.97 mg l^{-1}		1.19 mg l^{-1}			
			5.77 mg l^{-1}		2.25 mg l^{-1}			
			24.3 mg l^{-1}		1.45 mg l^{-1}			
			6.82 mg l^{-1}		1.08 mg l^{-1}			
			5.53 mg l^{-1}		4.13 mg l^{-1}		5.34 mg l^{-1}	
			20.6 mg l^{-1}		2.39 mg l^{-1}		3.29 mg l^{-1}	
			6.37 mg l^{-1}		2.34 mg l^{-1}		4.64 mg l^{-1}	
			6.04 mg l^{-1}		3.01 mg l^{-1}		2.87 mg l^{-1}	
			23.4 mg l^{-1}		1.00 mg l^{-1}		2.15 mg l^{-1}	
			6.81 mg l^{-1}		2.06 mg l^{-1}		3.28 mg l^{-1}	
			6.25 mg l^{-1}		2.93 mg l^{-1}		Not estimated	
			23.0 mg l^{-1}		1.68 mg l^{-1}			
			7.14 mg l^{-1}		2.12 mg l^{-1}			
			23.10 mg l^{-1}		2.93 mg l^{-1}		4.85 mg l^{-1}	
			27.8 mg l^{-1}		1.46 mg l^{-1}		1.53 mg l^{-1}	
			18.4 mg l^{-1}		2.96 mg l^{-1}		3.51 mg l^{-1}	
			8.34 mg l^{-1}		2.65 mg l^{-1}		2.54 mg l^{-1}	
			24.9 mg l^{-1}		1.09 mg l^{-1}		1.85 mg l^{-1}	
			8.9 mg l^{-1}		2.52 mg l^{-1}		2.58 mg l^{-1}	
			9.72 mg l^{-1}		2.23 mg l^{-1}		Not estimated	
			24.7 mg l^{-1}		1.23 mg l^{-1}			

Reference	Country	Site	DOC	POC	DIC	H CO_3 -C	Free CO_2	CH_4 - C
Dawson *et al.*, (2001a)	Scotland	Brocky Burn	8.81 mg l^{-1}		2.43 mg l^{-1}			
			7.64 mg l^{-1}		4.25 mg l^{-1}			
			20.4 mg l^{-1}		2.24 mg l^{-1}			
			6.59 mg l^{-1}		3.70 mg l^{-1}			
			9.25 mg l^{-1}	Not estimated	2.30 mg l^{-1}	Not estimated	1.97 mg l^{-1}	Not estimated
			24.6 mg l^{-1}		1.17 mg l^{-1}		1.03 mg l^{-1}	
			8.87 mg l^{-1}		2.27 mg l^{-1}		1.52 mg l^{-1}	
			9.58 mg l^{-1}		2.66 mg l^{-1}		1.80 mg l^{-1}	
			24.7 mg l^{-1}		0.94 mg l^{-1}		0.94 mg l^{-1}	
			9.92 mg l^{-1}		2.38 mg l^{-1}		1.96 mg l^{-1}	
			6.69 mg l^{-1}		1.85 mg l^{-1}		3.43 mg l^{-1}	
			24.2 mg l^{-1}		0.46 mg l^{-1}		1.61 mg l^{-1}	
			11.8 mg l^{-1}		0.85 mg l^{-1}		1.42 mg l^{-1}	
			25.3 mg l^{-1}		0.75 mg l^{-1}		Not estimated	
			10.7 mg l^{-1}		2.20 mg l^{-1}			
			10.01 mg l^{-1}		2.79 mg l^{-1}		1.9 mg l^{-1}	
			24.2 mg l^{-1}		1.09 mg l^{-1}		1.72 mg l^{-1}	
			10.5 mg l^{-1}		1.99 mg l^{-1}		2.19 mg l^{-1}	
			2.14 mg l^{-1}		5.26 mg l^{-1}		6.07 mg l^{-1}	
			12.8 mg l^{-1}		2.94 mg l^{-1}		4.35 mg l^{-1}	
			2.88 mg l^{-1}		4.04 mg l^{-1}		6.04 mg l^{-1}	
			7.98 mg l^{-1}		3.30 mg l^{-1}		Not estimated	
			22.9 mg l^{-1}		1.11 mg l^{-1}			
			8.76 mg l^{-1}		2.50 mg l^{-1}			
			8.82 mg l^{-1}		2.72 mg l^{-1}		0.32 mg l-1	
			23.8 mg l^{-1}		0.14 mg l^{-1}		0.38 mg l-1	
			8.96 mg l^{-1}		1.84 mg l^{-1}		0.36 mg l-1	
			30.2 mg l^{-1}		0.01 mg l^{-1}		0.47 mg l-1	
			8.80 mg l^{-1}		2.58 mg l^{-1}		Not estimated	
			24.1 mg l^{-1}		0.00 mg l^{-1}			
			9.26 mg l^{-1}		2.23 mg l^{-1}			
			7.59 mg l^{-1}		1.73 mg l^{-1}		0.23 mg l^{-1}	
			21.8 mg l^{-1}		0.00 mg l^{-1}		0.33 mg l^{-1}	
			8.60 mg l^{-1}		1.99 mg l^{-1}		0.30 mg l^{-1}	
			4.74 mg l^{-1}		0.29 mg l^{-1}		1.26 mg l^{-1}	
			7.31 mg l^{-1}		2.33 mg l^{-1}		Not estimated	
			19.5 mg l^{-1}		0.12 mg l^{-1}			
			8.40 mg l^{-1}		1.58 mg l^{-1}			
Miller *et al.*, (2001)	Scotland	Glensaugh Cairn	Mean 5.74 mg l^{-1} min 1.4 max 32.8	Not estimated	Not estimated	Not estimated	Not estimated	Not estimated
	England	Cottage Hill	Mean 17.68mg l^{-1} min 3.5 max 58.2					
	England	Rough Sike Upper	Mean 10.99 mg l^{-1} min 3.1 max 23.9					
	England	Trout Beck	Mean 8.82 mg l^{-1} min 2.0 max 26.2					
Hope *et al.*, (1997)	Scotland	River Dee	22.1 kg C ha^{-1} yr^{-1} (11.6) Method 2 28.4 kg C ha^{-1} yr^{-1} (6.1) Method 5	1.9 kg C ha^{-1} yr^{-1} (1.3) Method 2 2.4 kg C ha^{-1} yr^{-1} (1.0) Method 5	Not estimated	Not estimated	Not estimated	Not estimated

Reference	Country	Site	DOC	POC	DIC	H CO$_3$ -C	Free CO$_2$	CH$_4$ - C
Hope *et al.*, (1997)	Scotland	River Dee	21.1 kg C ha^{-1} yr^{-1} (11.1) Method 2	1.3 kg C ha^{-1} yr^{-1} (0.9) Method 2				
			27.5 kg C ha^{-1} yr^{-1} (6.5) Method 5	1.6 kg C ha^{-1} yr^{-1} (0.6) Method 5				
			19.8 kg C ha^{-1} yr^{-1} (9.4) Method 2,	1.4 kg C ha^{-1} yr^{-1} (1.5) Method 2				
			27.2 kg C ha^{-1} yr^{-1} (6.2) Method 5	1.9 kg C ha^{-1} yr^{-1} (1.4) Method 5				
Hope *et al.*, (1997)	Scotland	River Dee	20.4 kg C ha^{-1} yr^{-1} (11.1) Method 2	1.9 kg C ha^{-1} yr^{-1} (3.3) Method 2	Not estimated	Not estimated	Not estimated	Not estimated
			26.3 kg C ha^{-1} yr^{-1} (5.3) Method 5	2.4 kg C ha^{-1} yr^{-1} (2.2) Method 5				
			30.6 kg C ha^{-1} yr^{-1} (19.6) Method 2	2.5 kg C ha^{-1} yr^{-1} (2.2) Method 2				
			39.8 kg C ha^{-1} yr^{-1} (86.0) Method 5	3.2 kg C ha^{-1} yr^{-1} (13.8) Method 5				
			32.2 kg C ha^{-1} yr^{-1} (15.9) Method 2	4.5 kg C ha^{-1} yr^{-1} 1 (5.5) Method 2				
			38.8 kg C ha^{-1} yr^{-1} (7.0) Method 5	5.5 kg C ha^{-1} yr^{-1} (4.2) Method 5				
			27.2 kg C ha^{-1} yr^{-1} (18.1) Method 2	1.1 kg C ha^{-1} yr^{-1} 1 (1.3) Method 2				
			13.4 kg C ha^{-1} yr^{-1} (6.0) Method 2	1.2 kg C ha^{-1} yr^{-1} (1.7) Method 2				
			82.5 kg C ha^{-1} yr^{-1} (77.1) Method 2	14.3 kg C ha^{-1} yr^{-1} (20.9) Method 2				
			79.7 kg C ha^{-1} yr^{-1} (101.6) Method 2	13.6 kg C ha^{-1} yr^{-1} (25.7) Method 2				
			92.6 kg C ha^{-1} yr^{-1} (38.7) Method 5	15.8 kg C ha^{-1} yr^{-1} (13.1) Method 5				
			64.3 kg C ha^{-1} yr^{-1} (79.4) Method 2	9.7 kg C ha^{-1} yr^{-1} (17.2) Method 2				
			21.4 kg C ha^{-1} yr^{-1} (11.7) Method 2	1.5 kg C ha^{-1} yr^{-1} (1.7) Method 2				
			23.9 kg C ha^{-1} yr^{-1} (11.3) Method 2	1.0 kg C ha^{-1} yr^{-1} (0.7) Method 2				
			113.4 kg C ha^{-1} yr^{-1} (122.3) Method 2	3.5 kg C ha^{-1} yr^{-1} (55.7) Method 2				
			101.7 kg C ha^{-1} yr^{-1} (136.8) Method 2	85.3 kg C ha^{-1} yr^{-1} (184.5) Method 2				
			13.2 kg C ha^{-1} yr^{-1} (9.7) Method 2	1.0 kg C ha^{-1} yr^{-1} (1.6) Method 2				
			115.0 kg C ha^{-1} yr^{-1} (123.1) Method 2	21.3 kg C ha^{-1} yr^{-1} (32.6) Method 2				
			39.6 kg C ha^{-1} yr^{-1} (36.6) Method 2	2.5 kg C ha^{-1} yr^{-1} (3.0) Method 2				
			74.7 kg C ha^{-1} yr^{-1} (51.0) Method 2	5.4 kg C ha^{-1} yr^{-1} (6.4) Method 2				

Reference	**Country**	**Site**	**DOC**	**POC**	**DIC**	**H CO$_3$ -C**	**Free CO$_2$**	**CH$_4$ - C**
Hope *et al.*, (1997)	Scotland	River Don	18.2 kg C ha^{-1} yr^{-1} (19.4) Method 2	5.3 kg C ha^{-1} yr^{-1} (4.0) Method 2 5.5 kg C ha^{-1} yr^{-1} (2.6) Method 5	Not estimated	Not estimated	Not estimated	Not estimated
			19.4 kg C ha^{-1} yr^{-1} (11.6) Method 2	4.5 kg C ha^{-1} yr^{-1} (4.1) Method 2 4.6 kg C ha^{-1} yr^{-1} (2.3) Method 5				
			16.4 kg C ha^{-1} yr^{-1} (10.2) Method 2	4.0 kg C ha^{-1} yr^{-1} (3.2) Method 2 4.1 kg C ha^{-1} yr^{-1} (2.0) Method 5				
Hope *et al.*, (1997)	Scotland	River Don	7.kg C ha^{-1} yr^{-1} (3.5) Method 2	2.5 kg C ha^{-1} yr^{-1} (0.7) Method 2 2.8 kg C ha^{-1} yr^{-1} (0.5) Method 5				
* Hope and Billet (1997). (in Worrall *et al.*, 2003)	Scotland	River Halladale	103.4 kg C ha^{-1} yr^{-1}	Not estimated	Not estimated	Not estimated	Not estimated	Not estimated
Scott et al., (1998)	England	Great Dun Fell	15 g m^{-2} yr^{-1} 15 g m^{-2} yr^{-1} 7 g m^{-2} yr^{-1} 10 g m^{-2} yr^{-1} 11 g m^{-2} yr^{-1} 11 g m^{-2} yr^{-1} 7 g m^{-2} yr^{-1} 9 g m^{-2} yr^{-1}	Not estimated	Not estimated	Not estimated	Not estimated	Not estimated
Tipping et al., (1999)	England	Great Dun Fell and Newton Rigg	27.8 g C m^{-2} (5.1) sd, n=3 27.4 g C m^{-2} (4.2) sd n=6 56.3 g C m^{-2} (6.55) sd n=2 55.1 g C m^{-2} (15.8) sd n=3 56.8 g C m^{-2} (8.1) sd n=5 78.8 g C m^{-2} (12.7) sd n=3	Not estimated	Not estimated	Not estimated	Not estimated	Not estimated
Cole et al., (2002)	England	Hard Hill	16 mg l^{-1} low at 50cm depth 41.2 mg l^{-1} high at 10 cm depth 26.4 mg l^{-1} mean at 10 cm depth 18.6 mg l^{-1} mean at 50cm depth 7.1 g C m^{-2} yr^{-1} flux rate	Not estimated	Not estimated	Not estimated	Not estimated	Not estimated

Reference	Country	Site	DOC	POC	DIC	H CO$_3$ -C	Free CO$_2$	CH$_4$ - C
Monteith & Evans (2002)	Scotland	Loch Coire nan Arr	2.2 mg l^{-1} mean, 5.2 max, <0.1 min	Not estimated	Not estimated	Not estimated	Not estimated	Not estimated
	Scotland	Allt a 'Mharcaidh	2.3 mg l^{-1} mean 12.1 max <0.1 min					
	Scotland	Allt na Coire nan Con	3.9 mg l^{-1} mean 10.0 max <0.1 min					
	Scotland	Lochnagar	1.1 mg l^{-1} mean 3.4 max 0.2 min					
	Scotland	Loch Chon	3.2 mg l^{-1} mean 6.2 max 1.7 min					
	Scotland	Loch Tinker	4.7 mg l^{-1} mean 8.1 max 1.9 min					
	Scotland	Round Loch of Glenhead	3.0 mg l^{-1} mean 5.0 max 1.6 min					
	Scotland	Loch Grannoch	4.3 mg l^{-1} mean 12.8 max 2.7 min					
	Scotland	Dargall Lane	1.7 mg l^{-1} mean 5.9 max 0.3 min					
Monteith & Evans (2002)	England	Scoat Tarn	0.9 mg l^{-1} mean 2.7 max <0.1 min	Not estimated	Not estimated	Not estimated	Not estimated	Not estimated
	England	Burnmoor Tarn	2.0 mg l^{-1} mean 4.7 max 0.9 min					
	England	River Etherow	5.28 mg l^{-1} mean 34.0 max 0.3 min					
	England	Old Lodge	5.0 mg l^{-1} mean 15.0 max 1.7 min					
	England	Narrator Brook	1.4 mg l^{-1} mean 5.8 max 0.3 min					
	Wales	Llyn Llagi	2.4 mg l^{-1} mean 5.5 max <0.1 min					
	Wales	Llyn Cwm Mynach	2.6 mg l^{-1} mean 10.7 max <0.1 min					
	Wales	Afon Hafren	1.9 mg l^{-1} mean 8.1 max <0.1 min					
	Wales	Afon Gwy	2.12 mg l^{-1} mean 6.3 max <0.1 min					
	Northern Ireland	Beagh's Burn	11.1 mg l^{-1} mean 30.0 max 3.1 min					
	Northern Ireland	Bencrom River	4.1 mg l^{-1} mean 15.5 max 1.3 min					
	Northern Ireland	Blue Lough	3.5 mg l^{-1} mean 6.8 max 1.4 min					
	Northern Ireland	Coneyglen Burn	8.3 mg l^{-1} mean 26.9 max 1.7 min					

CH1 Appendix Table 4: Management and soil characteristics for studies in CH2 Appendix Table 5. * indicates information from a review article

Reference	Site Name	Catchment Soils	Management/Land Use
Dawson et al (2002)	Brocky Burn	Includes blanket peat	Burning for grouse
	Upper Hafren	Includes blanket peat	Grazing sheep
Worrall et al (2003)	Trout Beck	Mainly blanket peat	Not stated but known to be grazed and burnt
Dawson et al (2001b)	Brocky Burn	65% peat 25% peaty podzol	Burning for grouse
	Water of Dye	65% peat 25% peaty podzol	Burning for grouse
Dawson et al (2001a)	Brocky Burn	59% peat 22% peaty podzols 19% rankers <1% fluviosols	Burning for grouse
Miller et al (2001)	Glensaugh Cairn	Hill peats, peaty podzols, humus podzols	Rough grazing sheep and cattle
	Cottage Hill	98% peat	Erosion present and sheep grazed in summer
	Rough Sike Upper	97% peat	Erosion present and sheep grazed in summer
	Trout Beck	90% peat	Erosion present and sheep grazed in summer
Hope et al (1997)	River Dee	Peat at high alt to lowland till	Dee 12% wood, 63% upland grass/moor, 9% agric grass, 12% agric crop 4% other
Hope et al (1997)	River Don	Peat at high alt to lowland till	Don 10% wood, 30% upland grass/moor, 24% agric grass, 32% agric crop 4% other
* Hope and Billet (1997). (in Worrall *et al.*, 2003)	River Halladale	Not known	Not known
Scott et al (1998)	Great Dun Fell	Acid ranker and peat	Not stated
Tipping et al (1999)	Great Dun Fell and Newton Rigg	Peaty Gley	Not stated
Cole et al (2002)	Hard Hill	Peat	Not stated
Monteith and Evans (2000)	Loch Coire nan Arr	Peat	99% moorland 1% forestry
	Allt a 'Mharcaidh	Alpine, peaty podzols and blanket peat	98% moorland 2% native pine
	Allt na Coire nan Con	Peaty podzols, peaty gleys, peats	54% moorland 42% conifers 4% recently felled
	Lochnagar	Peats	100% alpine - moorland
	Loch Chon	Peaty gleys, peaty podzols	52% moorland, 44% conifers 4% recently felled
	Loch Tinker	Blanket peats	100% moorland
	Round Loch of Glenhead	Peat peaty podzols	100% moorland
	Loch Grannoch	Peats, peaty podzols, peaty gleys, skeletal soils	70% conifers, 30% moorland
	Dargall Lane	Podzols, peaty gleys, blanket peat	100% moorland
	Scoat Tarn	Shallow peaty rankers	100% moorland
	Burnmoor Tarn	Podzols, shallow peat, rankers	100% moorland
	River Etherow	Peaty podzols, blanket peat	100% moorland
	Old Lodge	Podzols	80% heathland, 15% deciduous woodland, 15% coniferous woodland
	Narrator Brook	Iron pan stagnopodzols, brown podzols	98% moorland acid grassland, 2% deciduous woodland
	Llyn Llagi	Stagnopodzols, stagnohumic gleys, blanket peat	100% moorland
	Llyn Cwm Mynach	Blanket peat, acid rankers	55% conifers, 55% moorland
	Afon Hafren	Podzols and organic peats	50% moorland, 50% conifers
	Afon Gwy	Peats, peaty podzols	100% moorland
	Beagh's Burn	Blanket peats	99% moorland 1% deciduous trees
	Bencrom River	Blanket peat	100% moorland
	Blue Lough	Blanket peat	100% moorland
	Coneyglen Burn	Blanket peat	95% moorland, 5% conifers

8.2 Chapter 2 Appendix

Below are tables of raw data from reviewed gaseous flux literature used in Chapter 2 for carbon dioxide (Clymo & Reddaway, 1971, 1972; Choularton et al., 1995; Clymo & Pearce, 1995; Fowler et al., 1995a; Fowler et al., 1995b; Nedwell & Watson, 1995; Beverland et al., 1996; Chapman & Thurlow, 1996; Fowler et al., 1996; Gallagher et al., 1996; Beswick et al., 1998; Chapman & Thurlow, 1998; Daulaut & Clymo, 1998; Hargreaves & Fowler, 1998; Lloyd et al., 1998; MacDonald et al., 1998; Moncrieff et al., 1998; Hughes et al., 1999; Freeman et al., 2002; Gauci et al., 2002; Hargreaves et al., 2003; Beckmann et al., 2004) and methane (Clymo & Reddaway, 1971, 1972; Choularton et al., 1995; Clymo & Pearce, 1995; Fowler et al., 1995a; Fowler et al., 1995b; Nedwell & Watson, 1995; Beverland et al., 1996; Chapman & Thurlow, 1996; Fowler et al., 1996; Gallagher et al., 1996; Beswick et al., 1998; Chapman & Thurlow, 1998; Daulaut & Clymo, 1998; Hargreaves & Fowler, 1998; Lloyd et al., 1998; MacDonald et al., 1998; Moncrieff et al., 1998; Hughes et al., 1999; Freeman et al., 2002; Gauci et al., 2002; Hargreaves et al., 2003; Beckmann et al., 2004).

Although not included in the review data on the recorded fluxes and concentrations of carbon species from river systems within peatland systems in the UK are also included here (Hope et al., 1997; Scott et al., 1998; Tipping et al., 1999; Monteith & Evans, 2000; Dawson et al., 2001a; Dawson et al., 2001b; Miller et al., 2001; Cole et al., 2002; Dawson et al., 2002; Worrall et al., 2003). These also include tabulated site characteristics for the river studies. Studies included in river export data tables are those who have not only attempted to estimate carbon exports within river catchments but also direct production within the soil environment. It should be noted that where authors have calculated annual river fluxes there is some dispute over which calculation methods should be used. Some methods produce systematic underestimates; others suffer from imprecision making it difficult to make comparisons between stations (Webb *et al.*, 1997). Further, it is difficult to compare concentration measurements (usually reported in mg l^{-1}) without adequate information such as stream are and discharge for use in flux calculation methods. Also there appear to be few studies concerned with assessing the error attached to riverine carbon fluxes (Hope *et al.*, 1997), therefore care should be taken when trying to interpret the results reported below.

Data from both gases fluxes and river exports are held in a Microsoft Access database available from the author on request.

CH2 Appendix Table 1: Published fluxes of methane from research on peatlands in the UK.

Reference	**Country**	**Site Name**	**Method**	**Bog Type**	**Management**	**Reported CH4 flux**
Beckman Sheppard and Lloyd (2004)	Scotland	Ellergower Moss	Peat cores static and dynamic chambers	Not stated	Not stated	341 µg h^{-1} m^{-2} Dark
						598 µg h^{-1} m^{-2} Dark
						695 µg h^{-1} m^{-2} Dark
						674 µg h^{-1} m^{-2} Light
						562 µg h^{-1} m^{-2} Light
						271 µg h^{-1} m^{-2} Light
Beswick *et al.* (1998)	Scotland	North Scotland	Aircraft	Blanket	N/A	48 µmol m^{-2} h^{-1}
Beverland *et al.* (1996)	Scotland	Strathy Bog	* Conditional sampling using GC 1	Blanket	Not stated	188 µmol m^{-2} h^{-1}
						106 µmol m^{-2} h^{-1}
						490 µmol m^{-2} h^{-1}
						572 µmol m^{-2} h^{-1}
			* Conditional sampling using GC 2			155 µmol m^{-2} h^{-1}
						343 µmol m^{-2} h^{-1}
						106 µmol m^{-2} h^{-1}
Beverland *et al.* (1996)	Scotland	Loch More	Conditional sampling	Blanket	Not stated	22.7 µmol m^{-2} h^{-1}
						14.7 µmol m^{-2} h^{-1}
Chapman and Thurlow (1996)	Scotland	Bad a Cheo	Static chamber	Blanket	Not stated	1.05 mg C m^{-2} h^{-1}
(Choularton *et al.*, 1995)	Scotland	Strathy Bog	Flux gradient Balloon	Blanket	Not stated	7-52 µmol m^{-2} h^{-1}night
			Nocturnal Box Model			101µmol m^{-2} h^{-1}night
						38 µmol m^{-2} h^{-1} night
						49 µmol m^{-2} h^{-1} night
		Loch More	Eddy correlation	Blanket	Not stated	15 µmol m^{-2} h^{-1} night
						40 µmol m^{-2} h^{-1} day
						30 µmol m^{-2} h^{-1} night
						39 µmol m^{-2} h^{-1} mean
			Relaxed Eddy correlation			15 µmol m^{-2} h^{-1} night
						22.7 µmol m^{-2} h^{-1} mean
						37 µmol m^{-2} h^{-1} day
						21 µmol m^{-2} h^{-1}night
						28 µmol m^{-2} h^{-1} mean
			Aircraft			79 µmol m^{-2} h^{-1} NE Scotland
						205 µmol m^{-2} h^{-1} SW-NE Scotland
						128 µmol m^{-2} h^{-1} NE Scotland
						270 µmol m^{-2} h^{-1} Scotland
Clymo and Pearce (1995)	Scotland	Ellergower Moss	Static chamber	Raised	Not stated	23 µmol m^{-2} h^{-1}
						62 µmol m^{-2} h^{-1}
Clymo and Reddaway (1971 and 1972)	England	Moor House Burnt Hill	Static chambers	Blanket	Not stated	0.07 g C dm^{-2} yr^{-1}
						0.04 g C dm^{-2} yr^{-1}
						0.01 g C dm^{-2} yr^{-1}

Reference	Country	Site Name	Method	Bog Type	Management	Reported CH4 flux
Daulat and Clymo (1998)	Scotland	Caithness	Cores	Blanket	Not stated	18 μmol m^{-2} h^{-1}
						46 μmol m^{-2} h^{-1}
						100 μmol m^{-2} h^{-1}
Fowler *et al.* (1995a)	Scotland	Loch More	Eddy covariance	Blanket	Not stated	38.6 μmol m^{-2} h^{-1}
			Monolith laboratory			111 μmol m^{-2} h^{-1}
						103 μmol m^{-2} h^{-1}
						8 μmol m^{-2} h^{-1}
Fowler *et al.* (1995b)	Scotland	Loch More	Eddy covariance	Blanket	Not stated	40.3 μmol m^{-2} h^{-1} Day
						30.2 μmol m^{-2} h^{-1} Night
						38.6 μmol m^{-2} h^{-1}
Fowler *et al.* (1996)	Scotland	Loch More	Vertical profile	Blanket	Not stated	34 - 45 μmol m^{-2} h^{-1}
			Tethered balloon			56 μmol m^{-2} h^{-1}
			Eddy covariance?			50-60 μmol m^{-2} h^{-1}
		Caithness	Aircraft			128 μmol m^{-2} h^{-1}
						270 μmol m^{-2} h^{-1}
						100 - 150 μmol m^{-2} h^{-1}
		Portree to Wick	Aircraft			52 μmol m^{-2} h^{-1}
Freeman *et al.* (2002)	Wales	Cerrig-yr-Wyn	Cores	Soligenous Gully Mire	Not stated	43 ng g (peat)$^{-1}$ h^{-1}
						6 ng g (peat)$^{-1}$ h^{-1}
						40 ng g (peat)$^{-1}$ h^{-1}
						99 ng g (peat)$^{-1}$ h^{-1}
Gallagher *et al.* (1994)	Scotland	Caithness	Aircraft	Blanket	Not stated	0.91 ± 0.51 μg m^{-2} s^{-1}
						0.45 ± 0.28 μg m^{-2} s^{-1} night
Gauci Dise and Fowler (2002)	Scotland	Moidach More	Static chambers	Raised	Pristine?? Unaffected by drainage or cutting	21.2 μmol m^{-2} d-1
						21.3 μmol m^{-2} d^{-1}
						21 μmol m^{-2} d^{-1}
						19.8 μmol m^{-2} d^{-1}
						23.8 μmol m^{-2} d^{-1}
						64.8 μmol m^{-2} d^{-1}
Hargreaves and Fowler (1998)	Scotland	Loch More	Eddy covariance	Blanket	Not stated	39 μmol m^{-2} h^{-1}
						40.3 μmol m^{-2} h^{-1} day
						30.2 μmol m^{-2} h^{-1} night
Hughes *et al.* (1999)	Wales	Cerrig-yr-Wyn	Static chambers	Soligenous Gully Mire	Not stated	280 mg CH_4 m^{-2} d^{-1} control peak emission
						90 mg CH_4 m^{-2} d^{-1} experiment peak emission
Lloyd *et al.* (1998)	Scotland	Ellergower Moss	Monolith laboratory	Raised	Not stated	35 μmol m^{-2} h^{-1} light
						17 μmol m^{-2} h^{-1} dark
						310 μmol m^{-2} h^{-1} light
						266 μmol m^{-2} h^{-1} dark
MacDonald *et al.* (1998)	Scotland	Loch More	Static chambers	Blanket	Not stated	1.5 μmol m^{-2} h^{-1}
						17.5 μmol m^{-2} h^{-1}
						128.8 μmol m^{-2} h^{-1}
						14.5 μmol m^{-2} h^{-1}1
						175.6 μmol m^{-2} h^{-1}
		Loch Calium	Monolith laboratory	Blanket	Not stated	78 μmol m^{-2} h^{-1}
						98.5 μmol m^{-2} h^{-1}
						8.4 μmol m^{-2} h^{-1}
						81 μmol m^{-2} h^{-1}
						11.3 μmol m^{-2} h^{-1}

Reference	Country	Site Name	Method	Bog Type	Management	Reported CH4 flux
MacDonald *et al.* (1998)	Scotland	Loch Calium	CONVIRONS Monoliths Laboratory	Blanket	None stated	55.1 µmol m^{-2} h^{-1} 21.9 µmol m^{-2} h^{-1} 50.2 µmol m^{-2} h^{-1}
Moncrieff *et al.* (1998)	Scotland	Strathy Bog	Conditional sampling	Blanket	Not stated	15 µmol m^{-2} h^{-1} 40 µmol m^{-2} h^{-1}
Nedwell and Watson (1995)	Scotland	Ellergower Moss	Monolith laboratory	Ombrotrophic Bog	Not stated	0.04 mmol C m^{-2} d^{-1} 1.4 mmol C m^{-2} d^{-1} 2.3 mmol C m^{-2} d^{-1} 0.003 mmol C m^{-2} d^{-1} 0.158 mmol C m^{-2} d^{-1} 0.336 mmol C m^{-2} d^{-1}

CH2 Appendix Table 2: Mean methane flux results from published papers examined by this thesis, units are µmol CH_4 m^{-2} s^{-1}. Note; n in column 5 relates to the number of reported values from which a study mean was derived.

Reference	**Site**	**Mean CH_4 flux**	**SE**	**n**	**Study duration**	**Winter incl.**	**Method**
Beckman Sheppard and Lloyd (2004)	Ellergower Moss	0.009	0.001	6	Not stated	Not stated	Peat cores static and dynamic chambers
Beswick et al (1998)	North Scotland	0.013	*	1	29 Nov 1994	Yes	Aircraft
Beverland et al (1996)	Loch More	0.005	0.001	2	29/07/1992, 02/08/1992, 04/08/1992 and 05/08/1992	No	Conditional sampling
Beverland et al (1996)	Strathy Bog	0.078	0.020	7	31 May - 8 June 1993	No	Conditional sampling
Chapman and Thurlow (1996)	Bad a Cheo	0.024	*	1	May 1991 - Nov 1992	Yes	Static chamber
Choularton et al (1995)	Loch More	0.019	0.005	15	1992	Not stated	Flux gradient Balloon Eddy correlation Relaxed Eddy correlation Aircraft Nocturnal Box Model
Choularton et al (1995)	Strathy Bog	0.015	0.008	3	1992-94	Not stated	Flux gradient Balloon, Nocturnal Box Model
Clymo and Pearce (1995)	Ellergower Moss	0.012	0.005	2	Not stated	Not stated	Static chamber
Clymo and Reddaway (1971 and 1972)	Moor House	0.011	0.004	3	Apr- Oct 1969 and winter	Yes	Static chamber
Daulat and Clymo (1998)	Caithness	0.015	0.007	3	Oct-Sept	No	Peat cores
Fowler et al (1995a)	Loch More	0.019	0.007	4	28th May 1993, May - June 1994, 3 weeks, 24th July	No	Eddy covariance, monoliths
Fowler et al (1995b)	Loch More	0.009	0.002	4	May - June 1994, 3 weeks	No	Eddy covariance
Fowler et al (1996)	Caithness	0.045	0.010	4	24th July 3rd June 1993	No	Aircraft
	Loch More	0.014	0.001	5	28th May 24th, July 1993	No	Vertical profile, tethered balloon, eddy covariance
	Portree to Wick	0.014	*	1	29-Nov-94	Yes?	Aircraft
Gallagher et al (1994)	Caithness	0.042	0.014	2	1992?	Not stated	Aircraft
Gauci Dise and Fowler (2002)	Moidach More	0.020	0.005	6	21/05/97-25/06/97, 02/07/97-17/12/97, 31/03/98-11/09/98	Yes	Static chambers
Hargreaves and Fowler (1998)	Loch More	0.010	0.001	3	26th May - 9th June 1994	No	Eddy covariance
Hughes et al (1999)	Cerrig-yr-Wyn	0.131	0.067	2	1992 - 1997 summer	No	Static chambers
Lloyd et al (1998)	Ellergower Moss	0.044	0.021181	4	Not stated	Not stated	Monolith laboratory
MacDonald et al (1998)	Loch Calium	0.014	0.003	8	31/5/94-20/6/94	No	Monolith laboratory
MacDonald et al (1998)	Loch More	0.019	0.010	5	10/92-11/92, 05/93-07/93, 08/95-09/95	N/A	Static chambers
Moncrieff et al (1998)	Loch More	0.011	*	1	Not stated	Not stated	Conditional sampling
Moncrieff et al (1998)	Strathy Bog	0.004	*	1	Not stated	Not stated	Conditional sampling
Nedwell and Watson (1995)	Ellergower Moss	0.001	0.001	6	Jan-Aug 1993	Yes	Monolith laboratory

CH2 Appendix Table 3: Carbon dioxide fluxes in common units from reviewed sources.

Reference	Site Name	Light Dark	μmol CO_2 m^{-2} s^{-1}	μg CO_2 m^{-2} s^{-1}
Beckman Sheppard and Lloyd (2004)	Ellergower Moss	Dark	0.024	3800.000
Beckman Sheppard and Lloyd (2004)	Ellergower Moss	Dark	0.125	19800.000
Beckman Sheppard and Lloyd (2004)	Ellergower Moss	Dark	0.142	22500.000
Beckman Sheppard and Lloyd (2004)	Ellergower Moss	Light	-0.057	-9000.000
Beckman Sheppard and Lloyd (2004)	Ellergower Moss	Light	0.119	18900.000
Beckman Sheppard and Lloyd (2004)	Ellergower Moss	Light	-0.106	-16800.000
Beverland et al (1996)	Loch More	Light	-2.778	-439900.000
Beverland et al (1996)	Loch More	Light	-8.333	-1319700.000
Beverland et al (1996)	Loch More	Dark	0.000	0.000
Beverland et al (1996)	Loch More	Dark	2.778	439900.000
Chapman and Thurlow (1996)	Glensaugh	Dark	0.232	36700.000
Chapman and Thurlow (1996)	Glensaugh	Dark	0.157	24900.000
Chapman and Thurlow (1998)	Shetland and on mainland	Dark	Not readily converted	Not readily converted
Clymo and Pearce (1995)	Ellergower Moss	Dark	0.086	13636.900
Clymo and Pearce (1995)	Ellergower Moss	Dark	0.035	5498.750
Clymo and Reddaway (1971 and 1972)	Moor House Burnt Hill	Dark	0.143	22600.000
Clymo and Reddaway (1971 and 1972)	Moor House Burnt Hill	Dark	0.081	12900.000
Clymo and Reddaway (1971 and 1972)	Moor House Burnt Hill	Dark	0.132	20900.000
Fowler et al (1995)	Loch More	Light	-1.000	-158364.000
Fowler et al (1995)	Loch More	Dark	0.611	96778.000
Hargreaves Milne and Cannell (2003)	Auchencorth Moss	Net rate	-0.002	-285.100
Lloyd et al (1998)	Ellergower Moss	Light	0.147	23314.700
Lloyd et al (1998)	Ellergower Moss	Dark	0.119	18915.700
Lloyd et al (1998)	Ellergower Moss	Light	1.261	199714.600
Lloyd et al (1998)	Ellergower Moss	Dark	1.025	162323.100

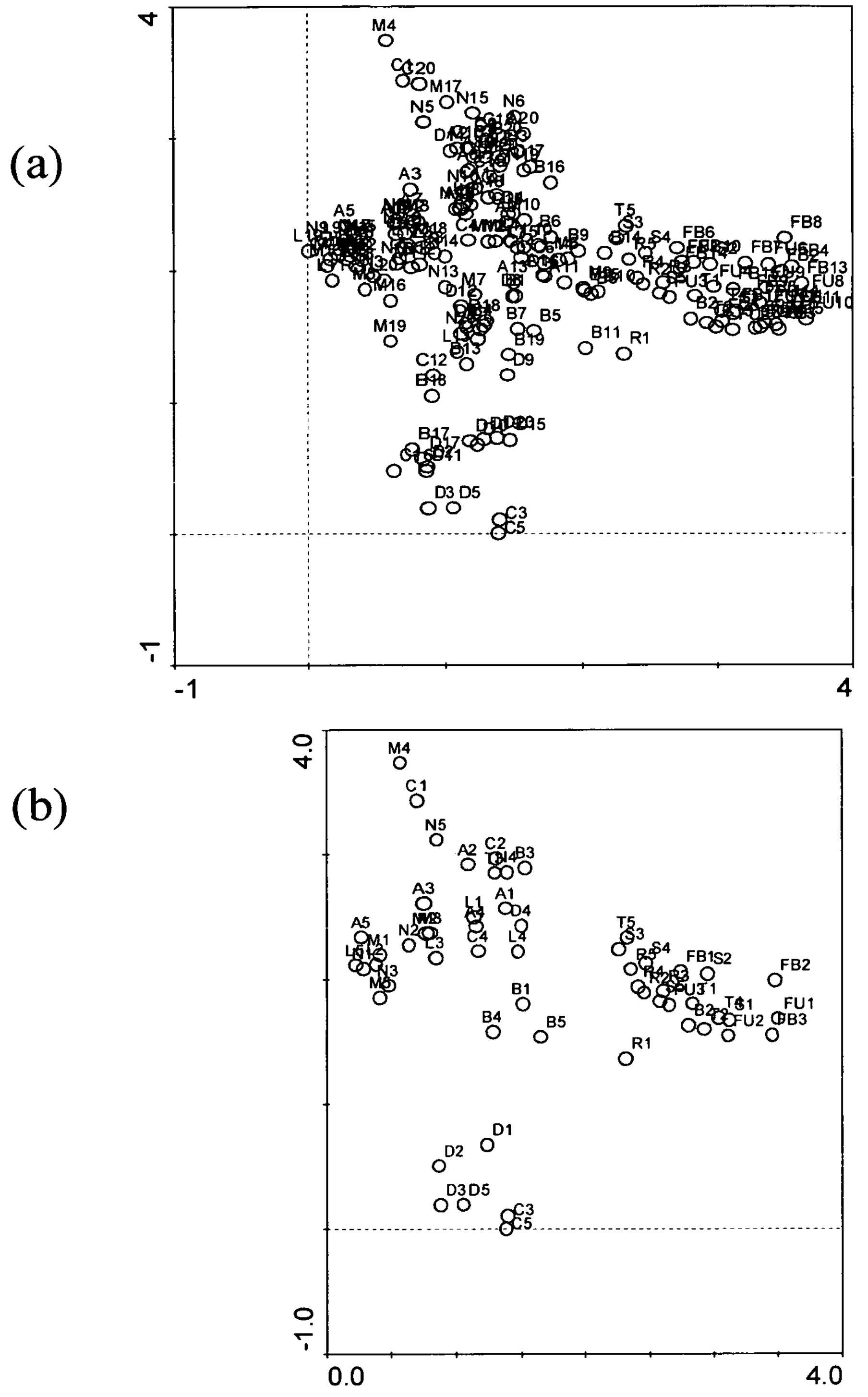
CH2 Appendix Table 4: Methane fluxes in common units from reviewed sources.

Reference	Site Name	μmol CH4 m^{-2} s^{-1}	μg CH4 m^{-2} s^{-1}
Beckman Sheppard and Lloyd (2004)	Ellergower Moss	0.006	0.095
Beckman Sheppard and Lloyd (2004)	Ellergower Moss	0.010	0.166
Beckman Sheppard and Lloyd (2004)	Ellergower Moss	0.012	0.193
Beckman Sheppard and Lloyd (2004)	Ellergower Moss	0.011	0.187
Beckman Sheppard and Lloyd (2004)	Ellergower Moss	0.010	0.156
Beckman Sheppard and Lloyd (2004)	Ellergower Moss	0.005	0.076
Beswick et al (1998)	North Scotland	0.013	0.218
Beverland et al (1996)	Strathy Bog	0.052	0.853
Beverland et al (1996)	Strathy Bog	0.029	0.481
Beverland et al (1996)	Strathy Bog	0.136	2.223
Beverland et al (1996)	Strathy Bog	0.159	2.599
Beverland et al (1996)	Strathy Bog	0.043	0.703
Beverland et al (1996)	Strathy Bog	0.095	1.556
Beverland et al (1996)	Strathy Bog	0.029	0.481
Beverland et al (1996)	Loch More	0.006	0.103
Beverland et al (1996)	Loch More	0.004	0.067
Chapman and Thurlow (1996)	Bad a Cheo	0.024	0.397
Choularton et al (1995)	Strathy Bog	0.002	0.032
Choularton et al (1995)	Strathy Bog	0.014	0.236
Choularton et al (1995)	Loch More	0.004	0.068
Choularton et al (1995)	Loch More	0.011	0.181
Choularton et al (1995)	Loch More	0.008	0.136
Choularton et al (1995)	Loch More	0.011	0.177
Choularton et al (1995)	Loch More	0.004	0.068
Choularton et al (1995)	Loch More	0.006	0.103
Choularton et al (1995)	Loch More	0.010	0.168
Choularton et al (1995)	Loch More	0.006	0.095
Choularton et al (1995)	Loch More	0.008	0.127
Choularton et al (1995)	Loch More	0.022	0.358
Choularton et al (1995)	Loch More	0.057	0.930
Choularton et al (1995)	Loch More	0.036	0.581
Choularton et al (1995)	Loch More	0.075	1.225
Choularton et al (1995)	Strathy Bog	0.028	0.458
Choularton et al (1995)	Loch More	0.011	0.172
Choularton et al (1995)	Loch More	0.014	0.222
Clymo and Pearce (1995)	Ellergower Moss	0.006	0.104
Clymo and Pearce (1995)	Ellergower Moss	0.017	0.281
Clymo and Reddaway (1971 and 1972)	Moor House Burnt Hill	0.018	0.302
Clymo and Reddaway (1971 and 1972)	Moor House Burnt Hill	0.011	0.172
Clymo and Reddaway (1971 and 1972)	Moor House Burnt Hill	0.003	0.043
Daulat and Clymo (1998)	Caithness	0.005	0.082
Daulat and Clymo (1998)	Caithness	0.013	0.209
Daulat and Clymo (1998)	Caithness	0.028	0.454
Fowler et al (1995a)	Loch More	0.011	0.175
Fowler et al (1995a)	Loch More	0.031	0.504

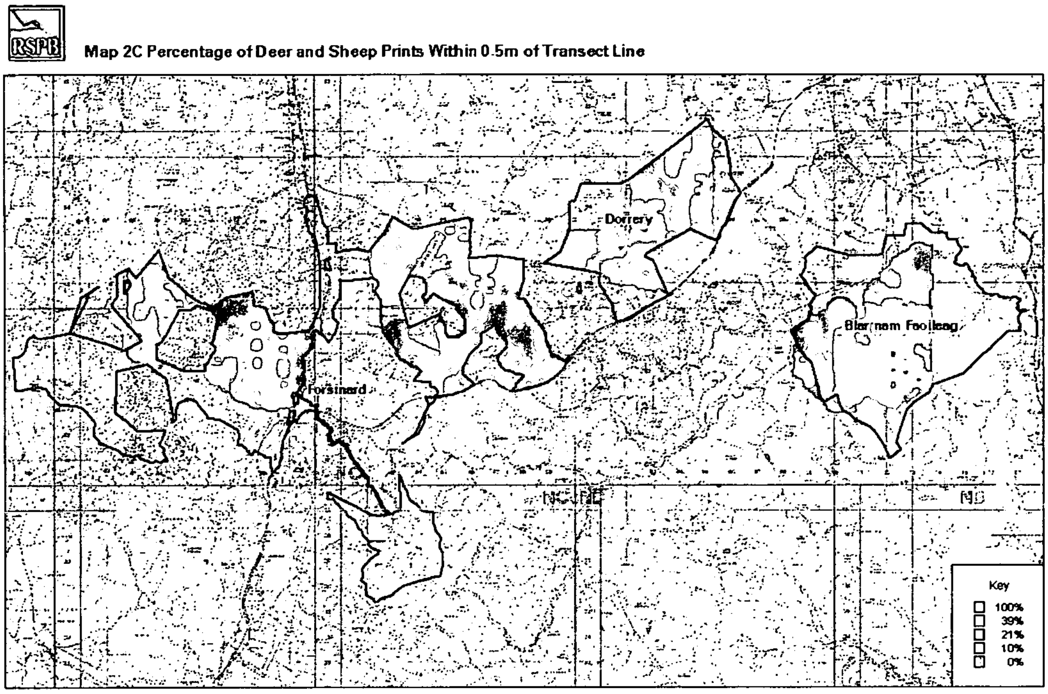
Reference	Site Name	µmol CH4 m^{-2} s^{-1}	µg CH4 m^{-2} s^{-1}
Fowler et al (1995a)	Loch More	0.029	0.467
Fowler et al (1995a)	Loch More	0.002	0.036
Fowler et al (1995b)	Loch More	0.011	0.183
Fowler et al (1995b)	Loch More	0.008	0.137
Fowler et al (1995b)	Loch More	0.011	0.175
Fowler et al (1995b)	Loch More	0.004	0.067
Fowler et al (1996)	Loch More	0.009	0.154
Fowler et al (1996)	Loch More	0.013	0.204
Fowler et al (1996)	Loch More	0.016	0.254
Fowler et al (1996)	Caithness	0.036	0.581
Fowler et al (1996)	Loch More	0.014	0.227
Fowler et al (1996)	Loch More	0.017	0.272
Fowler et al (1996)	Caithness	0.075	1.225
Fowler et al (1996)	Caithness	0.028	0.454
Fowler et al (1996)	Caithness	0.042	0.680
Fowler et al (1996)	Potree to Wick	0.014	0.236
Freeman et al (2002)	Cerrig-yr-Wyn	Not readily converted	Not readily converted
Freeman et al (2002)	Cerrig-yr-Wyn	Not readily converted	Not readily converted
Freeman et al (2002)	Cerrig-yr-Wyn	Not readily converted	Not readily converted
Freeman et al (2002)	Cerrig-yr-Wyn	Not readily converted	Not readily converted
Gallagher et al (1994)	Caithness	0.056	0.910
Gallagher et al (1994)	Caithness	0.028	0.450
Gauci Dise and Fowler (2002)	Moidach More	0.015	0.245
Gauci Dise and Fowler (2002)	Moidach More	0.015	0.247
Gauci Dise and Fowler (2002)	Moidach More	0.015	0.243
Gauci Dise and Fowler (2002)	Moidach More	0.014	0.229
Gauci Dise and Fowler (2002)	Moidach More	0.017	0.275
Gauci Dise and Fowler (2002)	Moidach More	0.046	0.750
Hargreaves and Fowler (1998)	Loch More	0.011	0.177
Hargreaves and Fowler (1998)	Loch More	0.011	0.183
Hargreaves and Fowler (1998)	Loch More	0.008	0.137
Hughes et al (1999)	Cerrig-yr-Wyn	0.198	3.241
Hughes et al (1999)	Cerrig-yr-Wyn	0.064	1.042
Lloyd et al (1998)	Ellergower Moss	0.010	0.159
Lloyd et al (1998)	Ellergower Moss	0.005	0.077
Lloyd et al (1998)	Ellergower Moss	0.086	1.406
Lloyd et al (1998)	Ellergower Moss	0.074	1.207
MacDonald et al (1998)	Loch More	0.000	0.007
MacDonald et al (1998)	Loch More	0.005	0.079
MacDonald et al (1998)	Loch More	0.036	0.584
MacDonald et al (1998)	Loch More	0.004	0.066
MacDonald et al (1998)	Loch More	0.049	0.797
MacDonald et al (1998)	Loch Calium	0.022	0.354
MacDonald et al (1998)	Loch Calium	0.027	0.447
MacDonald et al (1998)	Loch Calium	0.002	0.038
MacDonald et al (1998)	Loch Calium	0.023	0.367
MacDonald et al (1998)	Loch Calium	0.003	0.051

Reference	**Site Name**	**µmol CH4 m^{-2} s^{-1}**	**µg CH4 m^{-2} s^{-1}**
MacDonald et al (1998)	Loch Calium	0.015	0.250
MacDonald et al (1998)	Loch Calium	0.006	0.099
MacDonald et al (1998)	Loch Calium	0.014	0.228
Moncrieff et al (1998)	Strathy Bog	0.004	0.068
Moncrieff et al (1998)	Loch More	0.011	0.181
Nedwell and Watson (1995)	Ellergower Moss	0.000	0.001
Nedwell and Watson (1995)	Ellergower Moss	0.003	0.044
Nedwell and Watson (1995)	Ellergower Moss	0.004	0.072
Nedwell and Watson (1995)	Ellergower Moss	0.000	0.000
Nedwell and Watson (1995)	Ellergower Moss	0.000	0.005
Nedwell and Watson (1995)	Ellergower Moss	0.001	0.011

8.3 Chapter 3 Appendix



CH3 Appendix Figure 1: Axes 1 and 2 of DCA of samples from Forsinard vegetation relevés with (a) all samples and (b) only gas flux samples. Plot codes are as in Table 3.5. Axes 1 and 2 accounted for 13.1 % and 9.1 % respectively of total variation in vegetation data

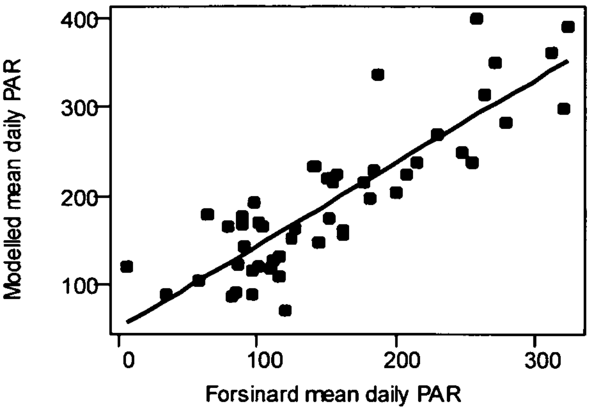


CH3 Appendix Figure 2: Deer and sheep footprints mapped across the Forsinard and Dorrery reserve.

8.4 Chapter 5 Appendix

CH5 Appendix Table 1: Missing value ordinary least squares regression model equations. Kin Temp = Kinbrace air temperature, Kin RH = Kinbrace relative humidity. Note: For PAR chamber temperature and relative humidity were modelled from Kinbrace data but soil temperature were measured on site.

Missing data	Modelled Regression Equation	R^2 adj %	p value	degrees of freedom
Air temperature	Chamber Temp = 0.683614 + (1.22216 * Kin Temp)	86.6	<0.001	12
Relative humidity	Chamber RH = 14.3692 + (0.873334 * Kin RH)	46.2	0.006	12
PAR	Chamber PAR = 530 + (30.4 * Chamber Temp) – (5.20 * Chamber RH) – (20.3 * Soil Temp)	74.6	<0.01	50

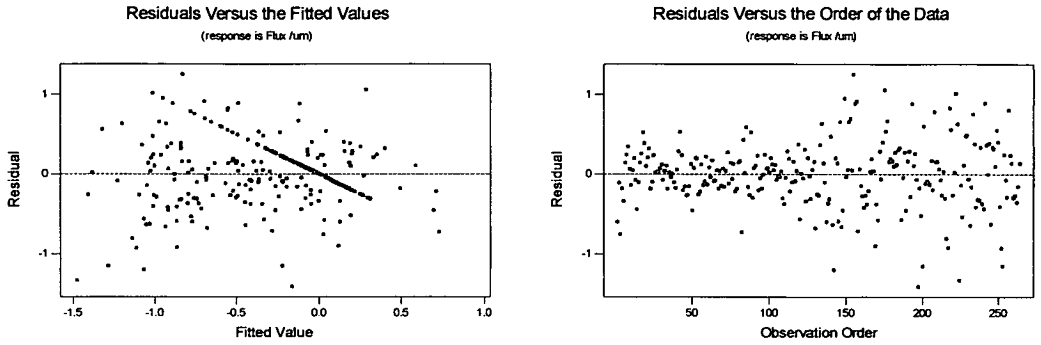


CH5 Appendix Figure 1: Forsinard daily mean PAR versus modelled daily PAR for the same days in 2004, R^2 adj = 73.6% n = 47 days.

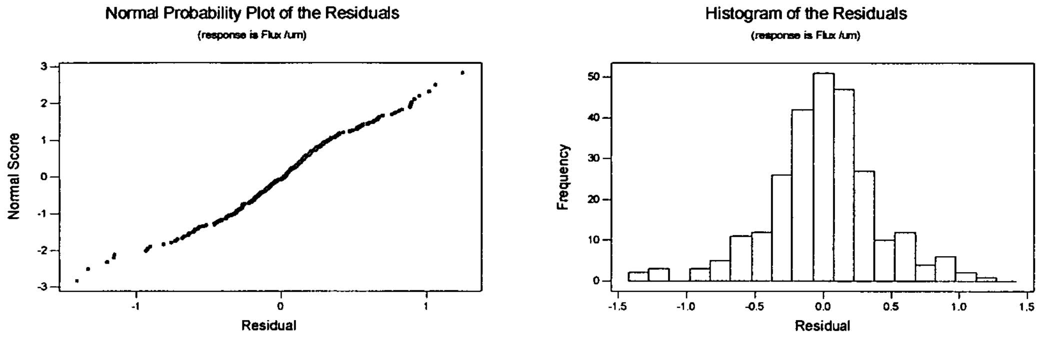
8.4.1 Minitab GLM Output

Below is the Minitab output for the modelled fluxes. Please note that Minitab does not compute all the sums of squares automatically, therefore some of these had to be computed by hand. These are identified as tabulated sum of squares using the combination of plot and interaction, and plot and site models. The most parsimonious model was used for determination of site or damage effects. For each model the effects of site environment interactions were first analysed, if these interactions were significant then they were retained in the model, however if these were not significant then the model without interactions was used. The one exception to this was the Main site 2003-4 dataset since this data had derived climate variables, the Main site 2005 dataset was used to identify the parsimonious model (which contained a site PAR interaction) the site effects for the 2003-4 data were thus analysed using the model with the site PAR interaction even though this was not significant in the 2003-4 dataset.

8.4.1a Main Sites 2003-4 CO2 Light Flux



Main sites 2003-4 CO_2 light residuals



Chapter 5 Appendix Figure 2: Residual plots for Main sites 2003-4 CO2 Light Flux

General Linear Model: Flux /µmols/m2/s versus Plot, Month

```
Analysis of Variance for Flux /um, using Adjusted SS for Tests

Source      DF     Seq SS     Adj SS     Adj MS      F      P
AT Leir      1     2.8801     0.0171     0.0171   0.09  0.767
AT Maol      1     6.3090     0.0136     0.0136   0.07  0.791
AT Nam i     1     0.0577     0.7945     0.7945   4.09  0.044
AT Slet      1     6.8057     0.0062     0.0062   0.03  0.858
RH Leir      1     0.3532     0.9347     0.9347   4.82  0.029
RH Maol      1     0.5009     0.8827     0.8827   4.55  0.034
RH Nam i     1     0.0458     0.0637     0.0637   0.33  0.567
RH Slet      1     3.5401     0.3163     0.3163   1.63  0.203
PAR Leir     1     3.8642     1.5465     1.5465   7.97  0.005
PAR Maol     1     0.0694     0.2151     0.2151   1.11  0.294
PAR Nam      1     0.1406     1.2975     1.2975   6.69  0.010
PAR SLet     1     0.7932     0.3479     0.3479   1.79  0.182
Plot        19    10.3921     7.6562     0.4030   2.08  0.007
Month        9    16.0104    16.0104     1.7789   9.17  0.000
Error      223    43.2733    43.2733     0.1941
Total      263    95.0358

Term           Coef    SE Coef       T      P
Constant    -1.1852     0.4990   -2.38  0.018
AT Leir     0.00786    0.02646    0.30  0.767
AT Maol    -0.00623    0.02350   -0.27  0.791
AT Nam i    0.05241    0.02590    2.02  0.044
AT Slet     0.00385    0.02157    0.18  0.858
RH Leir     0.02523    0.01149    2.19  0.029
RH Maol    0.014363   0.006735    2.13  0.034
RH Nam i  -0.002346   0.004093   -0.57  0.567
```

```
RH Slet      0.01390   0.01089      1.28  0.203
PAR Leir  -0.001747  0.000619     -2.82  0.005
PAR Maol  -0.000576  0.000547     -1.05  0.294
PAR Nam   -0.001840  0.000712     -2.59  0.010
PAR SLet  -0.001049  0.000783     -1.34  0.182

Unusual Observations for Flux /um

Obs  Flux /um        Fit      SE Fit  Residual    St Resid
 90   0.00000  -0.07967      0.31528   0.07967      0.26 X
142  -2.27282  -1.07138      0.19058  -1.20144     -3.03R
149   0.00000  -0.95172      0.12126   0.95172      2.25R
155   0.42123  -0.83163      0.12675   1.25286      2.97R
156   0.00000  -0.88804      0.19147   0.88804      2.24R
157   0.21927  -0.69706      0.14106   0.91633      2.20R
169  -0.78476   0.11924      0.13122  -0.90400     -2.15R
175   1.34200   0.28403      0.20756   1.05797      2.72R
193   0.76830  -0.11698      0.14287   0.88528      2.12R
197  -1.57557  -0.16219      0.13721  -1.41338     -3.38R
200  -1.37514  -0.22402      0.13205  -1.15112     -2.74R
217  -1.78736  -0.86678      0.13165  -0.92058     -2.19R
218   0.27860  -0.55308      0.22099   0.83168      2.18R
222   0.00000  -1.01545      0.20756   1.01545      2.61R
224  -2.80949  -1.47628      0.16914  -1.33321     -3.28R
241   0.40282  -0.49025      0.14797   0.89307      2.15R
252  -2.04697  -1.11393      0.18521  -0.93304     -2.33R
253  -2.44188  -1.28655      0.13273  -1.15533     -2.75R

R denotes an observation with a large standardized residual.
X denotes an observation whose X value gives it large influence.
```

General Linear Model: Flux /µmols/m2/s versus Plot, Month

```
Analysis of Variance for Flux /um, using Adjusted SS for Tests

Source      DF     Seq SS     Adj SS     Adj MS       F      P
RH Leir      1     1.1053     1.0489     1.0489    5.33  0.022
RH Maol      1     0.8191     0.6504     0.6504    3.30  0.070
RH Nam i     1     1.1893     0.0108     0.0108    0.06  0.815
RH Slet      1     6.8468     0.2919     0.2919    1.48  0.225
PAR Leir     1     6.3723     1.8138     1.8138    9.21  0.003
PAR Maol     1     2.7103     0.6344     0.6344    3.22  0.074
PAR Nam      1     0.0200     0.2454     0.2454    1.25  0.265
PAR SLet     1     4.0037     0.4690     0.4690    2.38  0.124
Air Temp     1     1.5519     0.0611     0.0611    0.31  0.578
Plot        19    10.0030     7.4409     0.3916    1.99  0.010
Month        9    15.9130    15.9130     1.7681    8.98  0.000
Error      226    44.5013    44.5013     0.1969
Total      263    95.0358

Term           Coef   SE Coef         T      P
Constant    -1.1617    0.4956     -2.34  0.020
RH Leir     0.02449   0.01061      2.31  0.022
RH Maol    0.012213  0.006720      1.82  0.070
RH Nam i  -0.000956  0.004076     -0.23  0.815
RH Slet     0.01316   0.01081      1.22  0.225
PAR Leir  -0.001671  0.000551     -3.04  0.003
PAR Maol  -0.000876  0.000488     -1.79  0.074
PAR Nam   -0.000524  0.000469     -1.12  0.265
PAR SLet  -0.001080  0.000700     -1.54  0.124
Air Temp    0.01089   0.01955      0.56  0.578

Unusual Observations for Flux /um

Obs  Flux /um        Fit      SE Fit  Residual    St Resid
```

```
 90   0.00000  -0.02587     0.31683   0.02587        0.08 X
122  -0.24235  -0.25745     0.29868   0.01510        0.05 X
134  -0.56688  -1.26520     0.27434   0.69832        2.00R
142  -2.27282  -1.02685     0.18746  -1.24597       -3.10R
149   0.00000  -0.89084     0.11321   0.89084        2.08R
155   0.42123  -0.83585     0.12649   1.25708        2.96R
156   0.00000  -0.89402     0.18870   0.89402        2.23R
157   0.21927  -0.70721     0.14194   0.92648        2.20R
175   1.34200   0.20372     0.20644   1.13828        2.90R
193   0.76830  -0.13070     0.13872   0.89900        2.13R
197  -1.57557  -0.17600     0.13425  -1.39957       -3.31R
200  -1.37514  -0.23586     0.12682  -1.13928       -2.68R
216  -1.95018  -1.10928     0.14928  -0.84090       -2.01R
217  -1.78736  -0.86931     0.13243  -0.91805       -2.17R
218   0.27860  -0.52333     0.21310   0.80193        2.06R
222   0.00000  -1.00165     0.20056   1.00165        2.53R
224  -2.80949  -1.45369     0.15474  -1.35579       -3.26R
241   0.40282  -0.56024     0.14549   0.96306        2.30R
252  -2.04697  -1.12845     0.18641  -0.91852       -2.28R
253  -2.44188  -1.28615     0.13160  -1.15572       -2.73R

R denotes an observation with a large standardized residual.
X denotes an observation whose X value gives it large influence.
```

Air temp site interaction

Model with interaction

```
Source      DF      Seq SS      Adj SS      Adj MS         F       P
Error      223     43.2733     43.2733      0.1941
```

Model without interaction

```
Source      DF      Seq SS      Adj SS      Adj MS         F       P
Error      226     44.5013     44.5013      0.1969
```

Combining these gives

```
Source      DF      Seq SS      Adj SS      Adj MS         F       P
Site.AT      3      1.2280      1.2280      0.4093      2.12  0.0985
Error      223     43.2733     43.2733      0.1941
```

Conclusion no site air temperature interaction

General Linear Model: Flux /µmols/m2/s versus Plot, Month

```
Analysis of Variance for Flux /um, using Adjusted SS for Tests

Source      DF      Seq SS      Adj SS      Adj MS        F      P
AT Leir      1      2.8801      0.0252      0.0252     0.13  0.722
AT Maol      1      6.3090      0.1036      0.1036     0.52  0.470
AT Nam i     1      0.0577      0.3720      0.3720     1.88  0.172
AT Slet      1      6.8057      0.0087      0.0087     0.04  0.834
PAR Leir     1      4.9870      3.3397      3.3397    16.87  0.000
PAR Maol     1      0.5661      0.4890      0.4890     2.47  0.117
PAR Nam      1      0.2842      0.6706      0.6706     3.39  0.067
PAR SLet     1      0.9194      0.6032      0.6032     3.05  0.082
RH           1      1.4545      0.3700      0.3700     1.87  0.173
Plot        19      6.9495      6.8862      0.3624     1.83  0.021
Month        9     19.0833     19.0833      2.1204    10.71  0.000
Error      226     44.7391     44.7391      0.1980
Total      263     95.0358

Term             Coef     SE Coef        T      P
Constant      -0.3247      0.3525    -0.92  0.358
AT Leir       0.00938     0.02629     0.36  0.722
AT Maol      -0.01669     0.02307    -0.72  0.470
```

```
AT Nam i     0.03472    0.02533       1.37  0.172
AT Slet     -0.00448    0.02138      -0.21  0.834
PAR Leir   -0.002267   0.000552      -4.11  0.000
PAR Maol   -0.000798   0.000508      -1.57  0.117
PAR Nam    -0.001259   0.000684      -1.84  0.067
PAR SLet   -0.001223   0.000701      -1.75  0.082
RH          0.004382   0.003205       1.37  0.173

Unusual Observations for Flux /um

Obs  Flux /um        Fit      SE Fit  Residual    St Resid
134  -0.56688   -1.26808     0.27813   0.70120       2.02R
142  -2.27282   -1.00402     0.18528  -1.26880      -3.14R
149   0.00000   -0.96790     0.12108   0.96790       2.26R
155   0.42123   -0.92263     0.12005   1.34386       3.14R
156   0.00000   -0.92987     0.19255   0.92987       2.32R
157   0.21927   -0.83935     0.12295   1.05862       2.48R
169  -0.78476    0.16491     0.13068  -0.94967      -2.23R
175   1.34200    0.25980     0.20935   1.08220       2.76R
193   0.76830   -0.17918     0.13552   0.94748       2.24R
197  -1.57557   -0.20525     0.13207  -1.37032      -3.23R
200  -1.37514   -0.22852     0.13103  -1.14662      -2.70R
216  -1.95018   -1.04559     0.13269  -0.90459      -2.13R
218   0.27860   -0.50091     0.21666   0.77951       2.01R
222   0.00000   -0.88954     0.19129   0.88954       2.21R
224  -2.80949   -1.32379     0.13741  -1.48570      -3.51R
241   0.40282   -0.52986     0.14636   0.93267       2.22R
252  -2.04697   -1.09369     0.18403  -0.95328      -2.35R
253  -2.44188   -1.21405     0.11801  -1.22783      -2.86R

R denotes an observation with a large standardized residual.
```

Site RH interaction

Model with interaction

```
Source      DF     Seq SS      Adj SS      Adj MS         F       P
Error      223    43.2733     43.2733      0.1941
```

Model without interaction

```
Source      DF     Seq SS      Adj SS      Adj MS         F       P
Error      226    44.7391     44.7391      0.1980
```

```
Combining these gives
Source      DF     Seq SS      Adj SS      Adj MS         F       P
Site.RH      3     1.4658      1.4658      0.4886      2.52  0.0588
Error      223    43.2733     43.2733      0.1941
```

Conclusion no interaction

General Linear Model: Flux /µmols/m2/s versus Plot, Month

```
Analysis of Variance for Flux /um, using Adjusted SS for Tests

Source      DF     Seq SS      Adj SS      Adj MS         F       P
AT Leir      1     2.8801      0.0012      0.0012      0.01   0.937
AT Maol      1     6.3090      0.0232      0.0232      0.12   0.730
AT Nam i     1     0.0577      0.7164      0.7164      3.69   0.056
AT Slet      1     6.8057      0.0460      0.0460      0.24   0.627
RH Leir      1     0.3532      1.7642      1.7642      9.08   0.003
RH Maol      1     0.5009      0.5129      0.5129      2.64   0.106
RH Nam i     1     0.0458      0.0127      0.0127      0.07   0.798
RH Slet      1     3.5401      0.3012      0.3012      1.55   0.214
PAR          1     2.9262      1.9956      1.9956     10.27   0.002
Plot        19    11.3611      8.6246      0.4539      2.34   0.002
Month        9    16.3427     16.3427      1.8159      9.35   0.000
```

```
Error      226    43.9133    43.9133     0.1943
Total      263    95.0358

Term           Coef    SE Coef        T      P
Constant    -1.1987     0.4707    -2.55  0.012
AT Leir     0.00207    0.02610     0.08  0.937
AT Maol     0.00753    0.02180     0.35  0.730
AT Nam i    0.03857    0.02009     1.92  0.056
AT Slet     0.00921    0.01892     0.49  0.627
RH Leir    0.030069   0.009979     3.01  0.003
RH Maol    0.009918   0.006105     1.62  0.106
RH Nam i  -0.000986   0.003856    -0.26  0.798
RH Slet    0.012130   0.009742     1.25  0.214
PAR       -0.001214   0.000379    -3.20  0.002

Unusual Observations for Flux /um

Obs  Flux /um       Fit     SE Fit  Residual   St Resid
 90   0.00000  -0.14071    0.31054   0.14071     0.45 X
134  -0.56688  -1.40887    0.24872   0.84199     2.31R
142  -2.27282  -1.05434    0.19004  -1.21848    -3.06R
149   0.00000  -0.93749    0.12101   0.93749     2.21R
155   0.42123  -0.82743    0.12667   1.24866     2.96R
156   0.00000  -0.91470    0.19016   0.91470     2.30R
157   0.21927  -0.69217    0.14070   0.91144     2.18R
169  -0.78476   0.07459    0.12838  -0.85935    -2.04R
175   1.34200   0.29694    0.20753   1.04506     2.69R
193   0.76830  -0.13345    0.14257   0.90174     2.16R
197  -1.57557  -0.17743    0.13694  -1.39813    -3.34R
200  -1.37514  -0.24558    0.13120  -1.12956    -2.68R
217  -1.78736  -0.85432    0.12854  -0.93303    -2.21R
218   0.27860  -0.52345    0.21921   0.80205     2.10R
222   0.00000  -1.04015    0.20630   1.04015     2.67R
224  -2.80949  -1.48932    0.16850  -1.32017    -3.24R
241   0.40282  -0.48627    0.14752   0.88908     2.14R
252  -2.04697  -1.14371    0.18419  -0.90326    -2.26R
253  -2.44188  -1.29651    0.13259  -1.14536    -2.72R

R denotes an observation with a large standardized residual.
X denotes an observation whose X value gives it large influence.
```

Site PAR interaction

Model with interaction

```
Source      DF     Seq SS     Adj SS      Adj MS        F       P
Error      223    43.2733    43.2733      0.1941
```

Model without interaction

```
Source      DF     Seq SS     Adj SS      Adj MS        F       P
Error      226    43.9133    43.9133      0.1943

Combining these gives
Source      DF     Seq SS     Adj SS      Adj MS        F       P
Site.PAR     3     0.6400     0.6400      0.2133    1.099  0.3504
Error      223    43.2733    43.2733      0.1941
```

Conclusion no interaction

General Linear Model: Flux /µmols/m2/s versus Plot, Month

```
Analysis of Variance for Flux /um, using Adjusted SS for Tests

Source      DF      Seq SS     Adj SS     Adj MS       F      P
Air Temp     1      9.4710     0.0006     0.0006    0.00  0.956
RH           1      1.6570     0.4283     0.4283    2.15  0.144
PAR Leir     1      5.5743     3.1774     3.1774   15.91  0.000
PAR Maol     1      2.9675     1.0759     1.0759    5.39  0.021
PAR Nam      1      1.9375     0.0570     0.0570    0.29  0.594
PAR SLet     1      1.9316     0.7520     0.7520    3.77  0.054
Plot        19      7.2099     6.8180     0.3588    1.80  0.024
Month        9     18.5633    18.5633     2.0626   10.33  0.000
Error      229     45.7237    45.7237     0.1997
Total      263     95.0358

Term             Coef    SE Coef        T      P
Constant      -0.3576     0.3496    -1.02  0.307
Air Temp      0.00107    0.01923     0.06  0.956
RH           0.004709   0.003215     1.46  0.144
PAR Leir    -0.002064   0.000517    -3.99  0.000
PAR Maol    -0.001059   0.000456    -2.32  0.021
PAR Nam     -0.000244   0.000457    -0.53  0.594
PAR SLet    -0.001232   0.000635    -1.94  0.054

Unusual Observations for Flux /um

Obs  Flux /um       Fit      SE Fit   Residual   St Resid
134  -0.56688  -1.32728    0.27280    0.76040      2.15R
142  -2.27282  -0.97269    0.18312   -1.30013     -3.19R
149   0.00000  -0.89405    0.11165    0.89405      2.07R
155   0.42123  -0.94702    0.11444    1.36825      3.17R
156   0.00000  -0.96546    0.18665    0.96546      2.38R
157   0.21927  -0.86612    0.11773    1.08539      2.52R
175   1.34200   0.19454    0.20780    1.14746      2.90R
193   0.76830  -0.23318    0.11976    1.00147      2.33R
197  -1.57557  -0.25408    0.12081   -1.32149     -3.07R
200  -1.37514  -0.27671    0.12013   -1.09843     -2.55R
216  -1.95018  -1.03728    0.13295   -0.91290     -2.14R
222   0.00000  -0.89454    0.19009    0.89454      2.21R
224  -2.80949  -1.32592    0.13376   -1.48357     -3.48R
241   0.40282  -0.57950    0.14407    0.98232      2.32R
252  -2.04697  -1.09727    0.18454   -0.94970     -2.33R
253  -2.44188  -1.21122    0.11849   -1.23066     -2.86R

R denotes an observation with a large standardized residual.
```

General Linear Model: Flux /µmols/m2/s versus Site, Month

```
Analysis of Variance for Flux /um, using Adjusted SS for Tests

Source      DF      Seq SS     Adj SS     Adj MS       F      P
Air Temp     1      9.4710     0.0115     0.0115    0.05  0.816
RH           1      1.6570     1.0725     1.0725    5.04  0.026
PAR Leir     1      5.5743     4.1053     4.1053   19.31  0.000
PAR Maol     1      2.9675     1.0770     1.0770    5.06  0.025
PAR Nam      1      1.9375     0.0093     0.0093    0.04  0.834
PAR SLet     1      1.9316     0.7329     0.7329    3.45  0.065
Site         3      0.8365     0.4418     0.1473    0.69  0.557
Month        9     18.5605    18.5605     2.0623    9.70  0.000
Error      245     52.0999    52.0999     0.2127
Total      263     95.0358

Term             Coef    SE Coef        T      P
Constant      -0.6422     0.3379    -1.90  0.059
Air Temp      0.00446    0.01918     0.23  0.816
RH           0.007034   0.003132     2.25  0.026
```

```
PAR Leir  -0.002281  0.000519    -4.39  0.000
PAR Maol  -0.001004  0.000446    -2.25  0.025
PAR Nam   -0.000096  0.000456    -0.21  0.834
PAR SLet  -0.001193  0.000642    -1.86  0.065

Unusual Observations for Flux /um

Obs  Flux /um       Fit      SE Fit  Residual    St Resid
 90   0.00000  -0.33135     0.26202   0.33135      0.87 X
117  -1.31939  -1.23869     0.23565  -0.08070     -0.20 X
122  -0.24235  -0.44079     0.27570   0.19844      0.54 X
129  -0.23893  -0.29566     0.23606   0.05673      0.14 X
134  -0.56688  -1.40121     0.26839   0.83433      2.22RX
135  -0.36779  -0.49912     0.22491   0.13133      0.33 X
142  -2.27282  -0.94792     0.12410  -1.32490     -2.98R
155   0.42123  -0.75252     0.10044   1.17375      2.61R
175   1.34200  -0.03090     0.15299   1.37290      3.16R
197  -1.57557  -0.06548     0.10779  -1.51009     -3.37R
200  -1.37514  -0.09418     0.10699  -1.28096     -2.86R
216  -1.95018  -0.98682     0.12234  -0.96336     -2.17R
217  -1.78736  -0.81772     0.10170  -0.96963     -2.16R
218   0.27860  -1.15492     0.12222   1.43352      3.22R
222   0.00000  -1.14322     0.11590   1.14322      2.56R
224  -2.80949  -1.19374     0.12152  -1.61575     -3.63R
226  -1.31517  -0.36398     0.11225  -0.95119     -2.13R
241   0.40282  -0.50179     0.13689   0.90461      2.05R
250   0.35611  -0.68285     0.10560   1.03897      2.31R
252  -2.04697  -0.85991     0.09813  -1.18706     -2.63R
253  -2.44188  -1.04911     0.10482  -1.39276     -3.10R

R denotes an observation with a large standardized residual.
X denotes an observation whose X value gives it large influence.
```

Site test

Model with Plot

```
Source       DF      Seq SS      Adj SS      Adj MS         F      P
Error       229     45.7237     45.7237      0.1997
```

Model with site

```
Source       DF      Seq SS      Adj SS      Adj MS         F      P
Error       245     52.0999     52.0999      0.2127
```

Combining these gives

```
Source       DF      Seq SS      Adj SS      Adj MS         F      P
Site          3     0.8365      0.4418      0.1473     0.370    0.7757
Plot(site)  16      6.3762      6.3762      0.3985
----------------------------------------------------------------------
Plot         19      7.2127      6.8180      0.3588     1.8      0.0238
```

Other effects

```
Residual    229     45.7237     45.7237      0.1997
```

General Linear Model: Flux /µmols/m2/s versus Damage, Month

```
Analysis of Variance for Flux /um, using Adjusted SS for Tests

Source      DF      Seq SS      Adj SS      Adj MS        F       P
Air Temp     1      9.4710      0.0597      0.0597     0.28   0.597
RH           1      1.6570      1.0669      1.0669     5.02   0.026
PAR Leir     1      5.5743      4.1281      4.1281    19.42   0.000
PAR Maol     1      2.9675      2.5551      2.5551    12.02   0.001
PAR Nam      1      1.9375      0.0335      0.0335     0.16   0.692
PAR SLet     1      1.9316      1.7213      1.7213     8.10   0.005
Damage       1      0.0040      0.0399      0.0399     0.19   0.665
Month        9     18.9912     18.9912      2.1101     9.93   0.000
```

```
Error      247    52.5017    52.5017     0.2126
Total      263    95.0358

Term            Coef   SE Coef        T      P
Constant     -0.6968    0.3291    -2.12  0.035
Air Temp     0.00932   0.01758     0.53  0.597
RH          0.007003  0.003126     2.24  0.026
PAR Leir   -0.001917  0.000435    -4.41  0.000
PAR Maol   -0.001323  0.000381    -3.47  0.001
PAR Nam    -0.000171  0.000431    -0.40  0.692
PAR SLet   -0.001208  0.000424    -2.85  0.005

Unusual Observations for Flux /um

Obs  Flux /um        Fit      SE Fit  Residual    St Resid
 90   0.00000   -0.33609     0.26184   0.33609      0.89 X
117  -1.31939   -1.10336     0.21124  -0.21603     -0.53 X
120  -1.63490   -0.75281     0.14343  -0.88208     -2.01R
122  -0.24235   -0.44935     0.27475   0.20700      0.56 X
129  -0.23893   -0.18833     0.21720  -0.05060     -0.12 X
134  -0.56688   -1.55711     0.24133   0.99023      2.52RX
135  -0.36779   -0.39512     0.21143   0.02733      0.07 X
142  -2.27282   -0.93090     0.12137  -1.34192     -3.02R
155   0.42123   -0.78686     0.09693   1.20810      2.68R
157   0.21927   -0.70630     0.09734   0.92557      2.05R
175   1.34200   -0.01996     0.15265   1.36195      3.13R
197  -1.57557   -0.10855     0.10204  -1.46702     -3.26R
200  -1.37514   -0.13485     0.10175  -1.24029     -2.76R
216  -1.95018   -1.01572     0.12006  -0.93446     -2.10R
217  -1.78736   -0.82882     0.10110  -0.95854     -2.13R
218   0.27860   -1.11171     0.11685   1.39031      3.12R
222   0.00000   -1.11306     0.11360   1.11306      2.49R
224  -2.80949   -1.15528     0.11777  -1.65421     -3.71R
226  -1.31517   -0.36425     0.11220  -0.95092     -2.13R
250   0.35611   -0.74224     0.09341   1.09835      2.43R
252  -2.04697   -0.88964     0.09514  -1.15733     -2.57R
253  -2.44188   -1.04633     0.10460  -1.39554     -3.11R

R denotes an observation with a large standardized residual.
X denotes an observation whose X value gives it large influence.
```

Damage test

Model with Plot

```
Source      DF     Seq SS     Adj SS     Adj MS        F       P
Error      229    45.7237    45.7237     0.1997
```

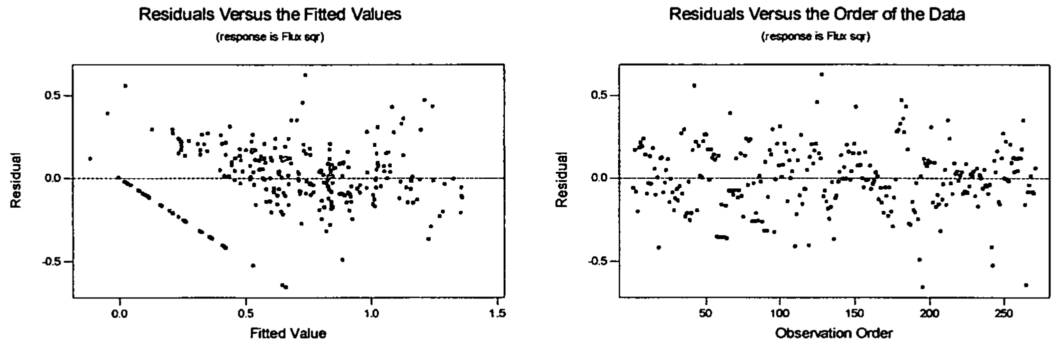
Model with Damage

```
Source      DF     Seq SS     Adj SS     Adj MS        F       P
Error      247    52.5017    52.5017     0.2126
```

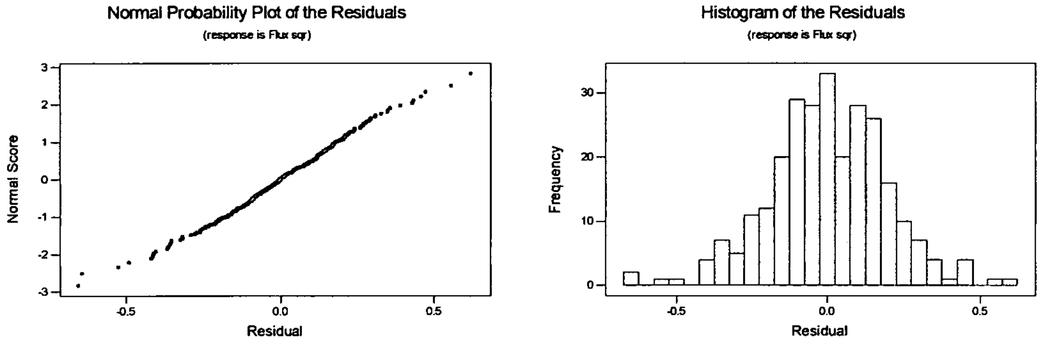
Combining these gives

```
Source      DF     Seq SS     Adj SS     Adj MS        F       P
Damage       1     0.0040     0.0399     0.0399    0.106  0.7485
Plot(Dama)  18     6.7780     6.7780     0.3766
```

8.4.1b Main sites 2003-4 CO_2 Dark Flux



Main sites 2003-4 CO_2 dark residuals



Chapter 5 Appendix Figure 3: Residual plots for Main sites 2003-4 CO_2 Dark Flux

General Linear Model: Flux sqroot versus Plot, Month

```
Analysis of Variance for Flux sqr, using Adjusted SS for Tests

Source      DF     Seq SS     Adj SS     Adj MS      F      P
ST Leir      1    1.24412    0.09750    0.09750   2.24  0.136
ST Maol      1    1.59750    0.06763    0.06763   1.55  0.214
ST Nam i     1   11.71567    0.13926    0.13926   3.20  0.075
ST Slet      1    6.34646    0.05154    0.05154   1.18  0.278
Plot        19    3.59497    3.02577    0.15925   3.65  0.000
Month        9    4.52495    4.52495    0.50277  11.54  0.000
Error      238   10.37160   10.37160    0.04358
Total      270   39.39527

Term          Coef   SE Coef      T      P
Constant   0.51587   0.08510   6.06  0.000
ST Leir    0.02194   0.01467   1.50  0.136
ST Maol    0.01491   0.01197   1.25  0.214
ST Nam i   0.01912   0.01070   1.79  0.075
ST Slet    0.01265   0.01163   1.09  0.278

Unusual Observations for Flux sqr

Obs  Flux sqr       Fit    SE Fit  Residual   St Resid
 18   0.00000   0.41874   0.07863  -0.41874     -2.17R
 42   0.57802   0.02197   0.08184   0.55605      2.90R
 66   0.34466  -0.04788   0.09854   0.39254      2.13R
110   0.00000   0.41215   0.07850  -0.41215     -2.13R
119   0.00000   0.40350   0.08215  -0.40350     -2.10R
125   1.18309   0.72537   0.05292   0.45772      2.27R
```

```
128   1.35910   0.73634    0.05155   0.62276      3.08R
136   0.86063   1.22804    0.17042  -0.36741     -3.05RX
151   1.51372   1.08325    0.08919   0.43047      2.28R
181   1.68317   1.21129    0.06236   0.47188      2.37R
184   1.67635   1.24241    0.06806   0.43394      2.20R
193   0.39185   0.88328    0.06226  -0.49143     -2.47R
195   0.00000   0.65631    0.08666  -0.65631     -3.46R
241   0.00000   0.41361    0.07823  -0.41361     -2.14R
242   0.00000   0.52633    0.04982  -0.52633     -2.60R
265   0.00000   0.64374    0.08150  -0.64374     -3.35R

R denotes an observation with a large standardized residual.
X denotes an observation whose X value gives it large influence.
```

General Linear Model: Flux sqroot versus Plot, Month

```
Analysis of Variance for Flux sqr, using Adjusted SS for Tests

Source     DF     Seq SS     Adj SS     Adj MS        F      P
Soil Tem    1   19.25498    0.10022    0.10022     2.32  0.129
Plot       19    5.09864    5.53971    0.29156     6.74  0.000
Month       9    4.61695    4.61695    0.51299    11.86  0.000
Error     241   10.42470   10.42470    0.04326
Total     270   39.39527

Term            Coef   SE Coef        T      P
Constant     0.53382   0.07728     6.91  0.000
Soil Tem     0.01524   0.01001     1.52  0.129

Unusual Observations for Flux sqr

Obs  Flux sqr       Fit      SE Fit  Residual    St Resid
 18   0.00000   0.41508     0.07788  -0.41508     -2.15R
 42   0.57802   0.01491     0.07791   0.56312      2.92R
 66   0.34466  -0.04900     0.09814   0.39365      2.15R
110   0.00000   0.40763     0.07788  -0.40763     -2.11R
119   0.00000   0.40335     0.08162  -0.40335     -2.11R
125   1.18309   0.73840     0.05053   0.44469      2.20R
128   1.35910   0.74602     0.05036   0.61308      3.04R
136   0.86063   1.17385     0.16241  -0.31323     -2.41RX
151   1.51372   1.10762     0.08182   0.40610      2.12R
181   1.68317   1.19570     0.05062   0.48747      2.42R
184   1.67635   1.22049     0.05475   0.45585      2.27R
193   0.39185   0.89826     0.04990  -0.50641     -2.51R
195   0.00000   0.67129     0.07807  -0.67129     -3.48R
241   0.00000   0.41280     0.07792  -0.41280     -2.14R
242   0.00000   0.52521     0.04962  -0.52521     -2.60R
265   0.00000   0.64217     0.08118  -0.64217     -3.35R

R denotes an observation with a large standardized residual.
X denotes an observation whose X value gives it large influence.
```

Site soil temperature interaction

Model with interaction

```
Source     DF     Seq SS     Adj SS     Adj MS        F      P
Error     238   10.37160   10.37160    0.04358
```

Model without interaction

```
Source     DF     Seq SS     Adj SS     Adj MS        F      P
Error     241   10.42470   10.42470    0.04326
```

Combining these gives

```
Source     DF     Seq SS     Adj SS     Adj MS        F      P
Site.ST     3     0.0531     0.0531     0.0177    0.406  0.7488
Error     238   10.37160   10.37160    0.04358
```

Conclusion no interaction

General Linear Model: Flux sqroot versus Site, Month

```
Analysis of Variance for Flux sqr, using Adjusted SS for Tests

Source      DF     Seq SS     Adj SS     Adj MS      F      P
Soil Tem     1    19.2550     0.0713     0.0713   1.41  0.236
Site         3     2.4316     3.0005     1.0002  19.83  0.000
Month        9     4.7448     4.7448     0.5272  10.45  0.000
Error      257    12.9639    12.9639     0.0504
Total      270    39.3953

Term           Coef   SE Coef       T      P
Constant    0.57998   0.08089    7.17  0.000
Soil Tem    0.01251   0.01053    1.19  0.236

Unusual Observations for Flux sqr

Obs  Flux sqr       Fit     SE Fit  Residual   St Resid
 18   0.00000   0.60104    0.04663  -0.60104     -2.74R
110   0.00000   0.57233    0.04660  -0.57233     -2.60R
119   0.00000   0.60853    0.04708  -0.60853     -2.77R
125   1.18309   0.70711    0.04683   0.47598      2.17R
128   1.35910   0.71337    0.04657   0.64573      2.94R
136   0.86063   1.06967    0.17172  -0.20904     -1.44 X
151   1.51372   1.03343    0.05736   0.48029      2.21R
181   1.68317   1.13209    0.04731   0.55108      2.51R
184   1.67635   1.15245    0.05308   0.52390      2.40R
193   0.39185   0.85461    0.04681  -0.46276     -2.11R
195   0.00000   0.85586    0.04691  -0.85586     -3.90R
207   0.50370   0.95382    0.04706  -0.45011     -2.05R
241   0.00000   0.49893    0.04679  -0.49893     -2.27R
242   0.00000   0.49393    0.04657  -0.49393     -2.25R
265   0.00000   0.79196    0.04673  -0.79196     -3.61R

R denotes an observation with a large standardized residual.
X denotes an observation whose X value gives it large influence.
```

Site test

Model with Plot

```
Source      DF      Seq SS      Adj SS      Adj MS       F       P
Error      241    10.42470    10.42470     0.04326
```

Model With Site

```
Source      DF      Seq SS      Adj SS      Adj MS       F       P
Error      257     12.9639     12.9639      0.0504
```

Combining these gives

```
Source      DF      Seq SS      Adj SS      Adj MS       F       P
Site         3      2.4316      3.0005      1.0002   6.302   0.005
Plot(site) 16       2.5392      2.5392      0.1587
---------------------------------------------------------------------
Plot        19     4.9708      5.5397      0.29156    6.74   <0.001
```

Other effects

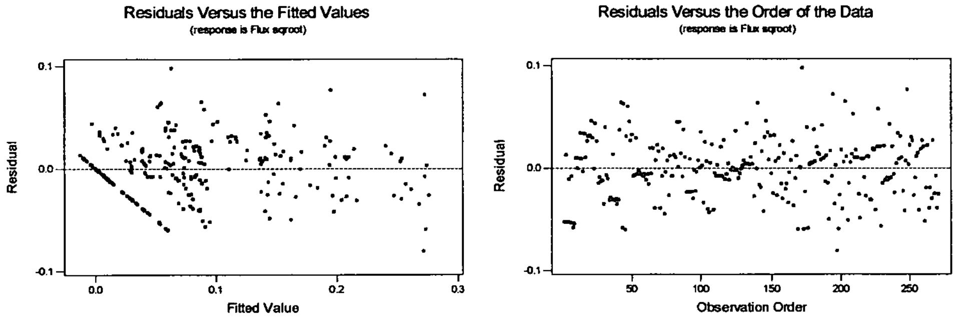
```
Error      241    10.42470    10.42470     0.04326
```

Descriptive Statistics: Flux sqroot by Site

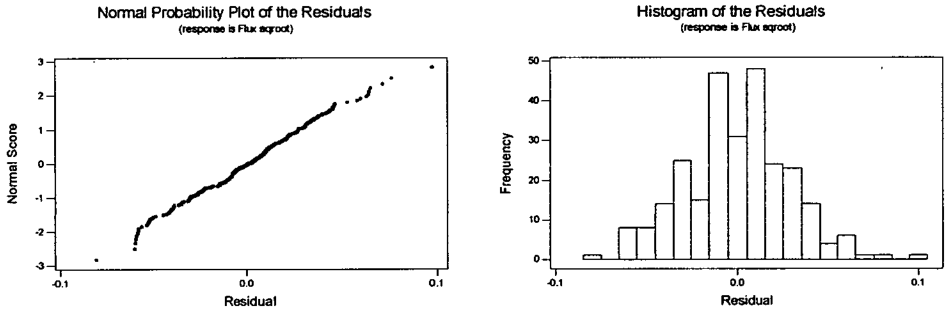
```
Variable  Site           N      Mean    Median    TrMean     StDev
Flux sqr  Leir          64    0.6988    0.7831    0.7030    0.3793
          Maol Don      71    0.6420    0.6837    0.6434    0.3720
          Nam Brea      64    0.8591    0.7823    0.8480    0.3128
          Sletill       72    0.4990    0.5061    0.4832    0.3749
```

```
Variable   Site        SE Mean    Minimum    Maximum        Q1         Q3
Flux sqr   Leir         0.0474     0.0000     1.3591    0.5128     0.9310
           Maol Don     0.0442     0.0000     1.3214    0.4477     0.9232
           Nam Brea     0.0391     0.0000     1.6832    0.6708     1.0372
           Sletill      0.0442     0.0000     1.5137    0.0000     0.7039
```

8.4.1c Main Sites 2003-4 CH4 Flux



Main sites 2003-4 CH_4 residuals



Chapter 5 Appendix Figure 4: Residual plots for Main sites 2003-4 CH_4 Flux

General Linear Model: Flux sqroot versus Plot, Month

```
Analysis of Variance for Flux sqr, using Adjusted SS for Tests

Source     DF     Seq SS     Adj SS     Adj MS       F      P
ST Leir     1   0.044160   0.001049   0.001049    1.79  0.182
ST Maol     1   0.812509   0.016783   0.016783   28.61  0.000
ST Nam i    1   0.003041   0.000000   0.000000    0.00  0.997
ST Slet     1   0.322727   0.012456   0.012456   21.24  0.000
WT Leir     1   0.017607   0.000464   0.000464    0.79  0.375
WT Maol     1   0.000081   0.000051   0.000051    0.09  0.768
WT Nam i    1   0.000025   0.000013   0.000013    0.02  0.884
WT Slet     1   0.006564   0.001243   0.001243    2.12  0.147
Plot       19   0.110988   0.086435   0.004549    7.76  0.000
Month       9   0.124007   0.124007   0.013779   23.49  0.000
Error     234   0.137252   0.137252   0.000587
Total     270   1.578961

Term           Coef    SE Coef        T      P
Constant    0.04244    0.01516     2.80  0.006
ST Leir    0.003190   0.002385     1.34  0.182
ST Maol    0.010419   0.001948     5.35  0.000
ST Nam i   0.000007   0.002046     0.00  0.997
ST Slet    0.008968   0.001946     4.61  0.000
WT Leir    0.000041   0.000047     0.89  0.375
WT Maol    0.000059   0.000199     0.30  0.768
WT Nam i  -0.000010   0.000070    -0.15  0.884
WT Slet    0.000129   0.000089     1.46  0.147
```

```
Unusual Observations for Flux sqr

Obs  Flux sqr        Fit       SE Fit  Residual    St Resid
  4  0.000000   0.015005   0.016123 -0.015005     -0.83 X
  5  0.000000   0.046869   0.006311 -0.046869     -2.00R
  8  0.000000   0.049559   0.006395 -0.049559     -2.12R
 29  0.000000   0.046431   0.018709 -0.046431     -3.02RX
 36  0.000000  -0.026765   0.016663  0.026765      1.52 X
 43  0.000000   0.080780   0.006927 -0.080780     -3.48R
 45  0.000000   0.082864   0.006835 -0.082864     -3.57R
 66  0.000000   0.050214   0.011451 -0.050214     -2.35R
169  0.000000   0.048252   0.006776 -0.048252     -2.08R
172  0.160789   0.091557   0.010101  0.069232      3.15R
173  0.000000   0.048253   0.006770 -0.048253     -2.08R
176  0.000000   0.048254   0.006776 -0.048254     -2.08R
194  0.344741   0.264212   0.007740  0.080529      3.51R
198  0.214691   0.262239   0.010357 -0.047548     -2.17R
248  0.271621   0.209003   0.007457  0.062618      2.72R

R denotes an observation with a large standardized residual.
X denotes an observation whose X value gives it large influence.
```

General Linear Model: Flux sqroot versus Plot, Month

```
Analysis of Variance for Flux sqr, using Adjusted SS for Tests

Source       DF     Seq SS     Adj SS      Adj MS        F       P
ST Leir       1   0.044160   0.001011    0.001011     1.74   0.189
ST Maol       1   0.812509   0.016603    0.016603    28.48   0.000
ST Nam i      1   0.003041   0.000002    0.000002     0.00   0.951
ST Slet       1   0.322727   0.012615    0.012615    21.64   0.000
Water Ta      1   0.020361   0.000660    0.000660     1.13   0.289
Plot         19   0.102919   0.095482    0.005025     8.62   0.000
Month         9   0.135080   0.135080    0.015009    25.75   0.000
Error       237   0.138163   0.138163    0.000583
Total       270   1.578961

Term            Coef    SE Coef        T       P
Constant     0.04187    0.01510     2.77   0.006
ST Leir     0.003118   0.002367     1.32   0.189
ST Maol     0.010355   0.001940     5.34   0.000
ST Nam i    0.000124   0.002028     0.06   0.951
ST Slet     0.008991   0.001933     4.65   0.000
Water Ta    0.000039   0.000037     1.06   0.289

Unusual Observations for Flux sqr

Obs  Flux sqr        Fit      SE Fit  Residual    St Resid
  5  0.000000   0.047322   0.006077 -0.047322     -2.03R
  8  0.000000   0.050020   0.006151 -0.050020     -2.14R
 43  0.000000   0.079942   0.006608 -0.079942     -3.44R
 45  0.000000   0.082013   0.006512 -0.082013     -3.53R
 52  0.000000   0.044563   0.009936 -0.044563     -2.03R
 66  0.000000   0.050673   0.011410 -0.050673     -2.38R
169  0.000000   0.048001   0.006705 -0.048001     -2.07R
172  0.160789   0.091735   0.010020  0.069054      3.14R
173  0.000000   0.048013   0.006696 -0.048013     -2.07R
176  0.000000   0.048038   0.006698 -0.048038     -2.07R
194  0.344741   0.264652   0.007364  0.080089      3.48R
198  0.214691   0.263078   0.010118 -0.048388     -2.21R
248  0.271621   0.208932   0.005815  0.062689      2.68R

R denotes an observation with a large standardized residual.
```

Test of site water table interaction

Model with interaction

```
Source     DF      Seq SS      Adj SS      Adj MS         F       P
Error     234    0.137252    0.137252    0.000587
```

Model without interaction

```
Source     DF      Seq SS      Adj SS      Adj MS         F       P
Error     237    0.138163    0.138163    0.000583
```

Combining these gives

```
Source     DF      Seq SS      Adj SS      Adj MS         F       P
Site.WT     3    0.000911    0.000911    0.000304     0.602  0.6143
Error     234    0.137252    0.137252    0.000587
```

Conclusion No site water table interaction

General Linear Model: Flux sqroot versus Plot, Month

```
Analysis of Variance for Flux sqr, using Adjusted SS for Tests

Source      DF      Seq SS      Adj SS      Adj MS        F       P
WT Leir      1    0.129278    0.000268    0.000268     0.31   0.580
WT Maol      1    0.133126    0.002311    0.002311     2.65   0.105
WT Nam i     1    0.089094    0.005551    0.005551     6.36   0.012
WT Slet      1    0.028759    0.002941    0.002941     3.37   0.068
Soil Tem     1    0.476332    0.017497    0.017497    20.04   0.000
Plot        19    0.398450    0.350351    0.018440    21.12   0.000
Month        9    0.117020    0.117020    0.013002    14.89   0.000
Error      237    0.206902    0.206902    0.000873
Total      270    1.578961

Term             Coef    SE Coef          T       P
Constant      0.01474    0.01687       0.87   0.383
WT Leir      0.000030   0.000055       0.55   0.580
WT Maol      0.000388   0.000239       1.63   0.105
WT Nam i     0.000204   0.000081       2.52   0.012
WT Slet      0.000198   0.000108       1.84   0.068
Soil Tem     0.009926   0.002217       4.48   0.000

Unusual Observations for Flux sqr

Obs  Flux sqr        Fit       SE Fit   Residual    St Resid
  4  0.000000   0.012291     0.019653  -0.012291      -0.56 X
  8  0.000000   0.057358     0.007728  -0.057358      -2.01R
 29  0.000000  -0.015651     0.021510   0.015651       0.77 X
 30  0.056388  -0.001859     0.012109   0.058248       2.16R
 36  0.000000  -0.028457     0.020217   0.028457       1.32 X
 43  0.000000   0.100743     0.007482  -0.100743      -3.52R
 45  0.000000   0.102728     0.007404  -0.102728      -3.59R
103  0.051984  -0.008642     0.011660   0.060627       2.23R
169  0.000000   0.072696     0.007396  -0.072696      -2.54R
173  0.000000   0.073689     0.007354  -0.073689      -2.58R
176  0.000000   0.075674     0.007288  -0.075674      -2.64R
194  0.344741   0.239944     0.008229   0.104796       3.69R
208  0.163320   0.108224     0.012838   0.055096       2.07R

R denotes an observation with a large standardized residual.
X denotes an observation whose X value gives it large influence.
```

Test of site water table interaction

Model with interaction

```
Source      DF      Seq SS      Adj SS      Adj MS         F        P
Error      234    0.137252    0.137252    0.000587
```

Model without interaction

```
Source      DF      Seq SS      Adj SS      Adj MS         F        P
Error      237    0.206902    0.206902    0.000873
```

Combining these gives

```
Source      DF      Seq SS      Adj SS      Adj MS         F        P
Site.ST      3    0.069650    0.069650    0.023217     39.55
Error      234    0.137252    0.137252    0.000587
```

Conclusion site soil temperature interaction

General Linear Model: Flux sqroot versus Site, Month

```
Analysis of Variance for Flux sqr, using Adjusted SS for Tests

Source       DF      Seq SS      Adj SS      Adj MS        F       P
ST Leir       1    0.044160    0.000134    0.000134     0.18   0.673
ST Maol       1    0.812509    0.011706    0.011706    15.58   0.000
ST Nam i      1    0.003041    0.000591    0.000591     0.79   0.376
ST Slet       1    0.322727    0.008533    0.008533    11.36   0.001
Water Ta      1    0.020361    0.000489    0.000489     0.65   0.421
Site          3    0.040820    0.043542    0.014514    19.32   0.000
Month         9    0.145239    0.145239    0.016138    21.48   0.000
Error       253    0.190104    0.190104    0.000751
Total       270    1.578961

Term             Coef    SE Coef          T        P
Constant      0.05626    0.01649       3.41    0.001
ST Leir      0.001098   0.002597       0.42    0.673
ST Maol      0.008299   0.002103       3.95    0.000
ST Nam i    -0.001927   0.002173      -0.89    0.376
ST Slet      0.007062   0.002096       3.37    0.001
Water Ta     0.000024   0.000030       0.81    0.421

Unusual Observations for Flux sqr

Obs   Flux sqr        Fit       SE Fit  Residual     St Resid
 43   0.000000   0.079193     0.006843 -0.079193       -2.98R
 45   0.000000   0.080853     0.006712 -0.080853       -3.04R
169   0.000000   0.058366     0.006750 -0.058366       -2.20R
172   0.160789   0.058700     0.006797  0.102090        3.84R
173   0.000000   0.058173     0.006741 -0.058173       -2.19R
176   0.000000   0.057787     0.006744 -0.057787       -2.17R
191   0.111933   0.164935     0.007441 -0.053002       -2.01R
194   0.344741   0.260018     0.007679  0.084723        3.22R
197   0.191599   0.259188     0.007633 -0.067589       -2.57R
203   0.153266   0.091720     0.007624  0.061546        2.34R
209   0.194590   0.135509     0.005994  0.059081        2.21R
227   0.148448   0.084485     0.006067  0.063963        2.39R
248   0.271621   0.205664     0.005726  0.065957        2.46R

R denotes an observation with a large standardized residual.
```

Model with plot

```
Source      DF      Seq SS      Adj SS      Adj MS         F        P
Error      237    0.138163    0.138163    0.000583
```

Model with site

```
Source      DF      Seq SS      Adj SS      Adj MS         F        P
Error      253    0.190104    0.190104    0.000751
```

Combining these gives

```
Source       DF     Seq SS      Adj SS      Adj MS         F       P
Site          3   0.040820    0.043542    0.014514      4.47  0.0184
Plot(site)   16   0.051941    0.051941    0.003246
------------------------------------------------------------------------
Plot         19   0.092761    0.095483    0.005025      8.62  < 0.001
```

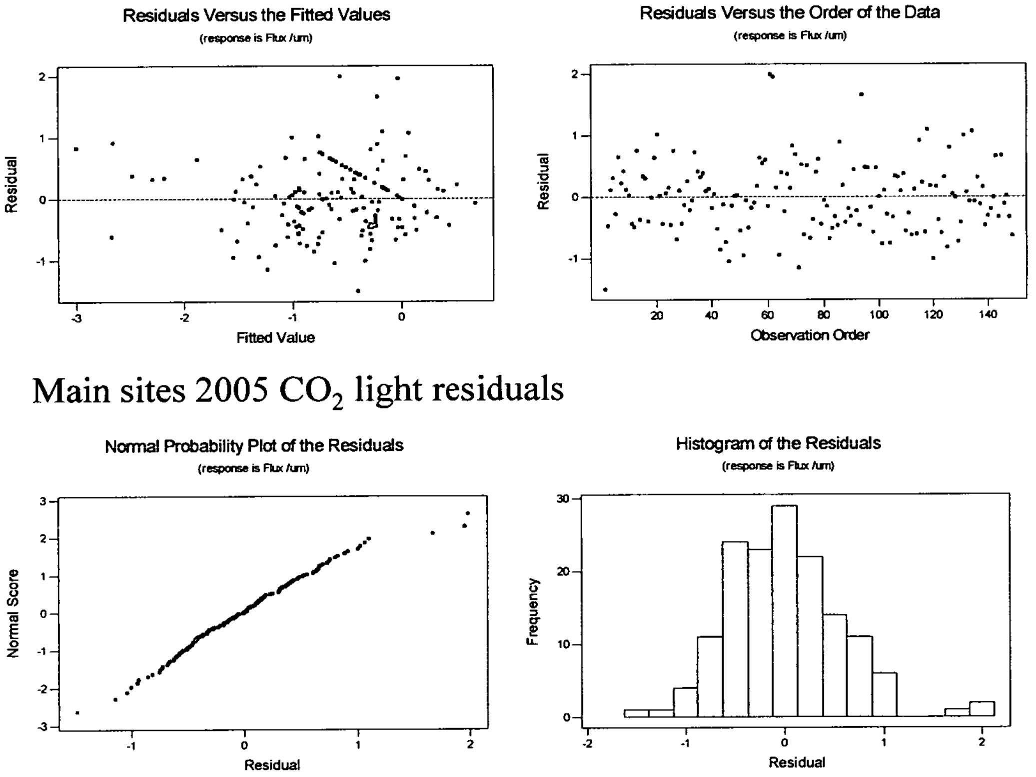
Other effects

```
Residual    237   0.138163    0.138163    0.000583
```

Descriptive Statistics: Flux sqroot by Site

```
Variable   Site              N      Mean    Median    TrMean     StDev
Flux sqr   Leir             64   0.04555   0.04064   0.04292   0.04570
           Maol Don         71   0.16318   0.16576   0.16325   0.07070
           Nam Brea         64   0.03889   0.03696   0.03642   0.03625
           Sletill          72   0.08004   0.05738   0.07802   0.06956
Variable   Site        SE Mean   Minimum   Maximum        Q1        Q3
Flux sqr   Leir        0.00571   0.00000   0.15327   0.00000   0.09105
           Maol Don    0.00839   0.00000   0.34474   0.10376   0.22090
           Nam Brea    0.00453   0.00000   0.16079   0.00000   0.05942
           Sletill     0.00820   0.00000   0.20632   0.00000   0.14730
```

8.4.1d Main Sites 2005 CO2 Light Flux



Chapter 5 Appendix Figure 5: Residual plots for Main sites 2005 CO_2 Light Flux

General Linear Model: Flux /µmols/m2/s versus Plot, Month

```
Analysis of Variance for Flux /um, using Adjusted SS for Tests

Source     DF     Seq SS     Adj SS     Adj MS        F       P
AT Leir     1     0.0001     2.2073     2.2073     5.23   0.024
AT Maol     1     7.1216     0.2763     0.2763     0.66   0.420
```

```
AT Nam i      1     1.4308     0.3185     0.3185    0.76  0.387
AT Slet       1     3.4792     0.1137     0.1137    0.27  0.605
RH Leir       1     1.8820     0.0000     0.0000    0.00  0.993
RH Maol       1     3.7948     0.0070     0.0070    0.02  0.898
RH Nam i      1     0.0151     0.0335     0.0335    0.08  0.779
RH Slet       1     0.5248     0.7124     0.7124    1.69  0.196
PAR Leir      1    12.8188     8.5075     8.5075   20.17  0.000
PAR Maol      1    10.0835     4.7914     4.7914   11.36  0.001
PAR Nam       1     1.3732     1.5709     1.5709    3.72  0.056
PAR SLet      1     3.5334     4.1471     4.1471    9.83  0.002
Plot         19    10.4442    10.6303     0.5595    1.33  0.181
Month         4     3.3196     3.3196     0.8299    1.97  0.104
Error       113    47.6670    47.6670     0.4218
Total       148   107.4881

Term             Coef   SE Coef       T      P
Constant        0.862     1.261    0.68  0.496
AT Leir       0.09854   0.04308    2.29  0.024
AT Maol      -0.05484   0.06776   -0.81  0.420
AT Nam i      0.03733   0.04296    0.87  0.387
AT Slet      -0.03041   0.05859   -0.52  0.605
RH Leir       0.00018   0.01909    0.01  0.993
RH Maol      -0.00236   0.01831   -0.13  0.898
RH Nam i      0.00553   0.01963    0.28  0.779
RH Slet      -0.04350   0.03348   -1.30  0.196
PAR Leir    -0.003818  0.000850   -4.49  0.000
PAR Maol    -0.002269  0.000673   -3.37  0.001
PAR Nam     -0.000940  0.000487   -1.93  0.056
PAR SLet    -0.001807  0.000576   -3.14  0.002

Unusual Observations for Flux /um

Obs  Flux /um        Fit    SE Fit  Residual  St Resid
  1  -1.90317   -0.40590   0.25581  -1.49726    -2.51R
 20   0.26120   -0.76156   0.45304   1.02276     2.20R
 61   1.42288   -0.56492   0.21672   1.98780     3.25R
 62   1.92274   -0.03148   0.27260   1.95423     3.32R
 71  -2.38314   -1.23384   0.33645  -1.14930    -2.07R
 94   1.43030   -0.23151   0.24114   1.66180     2.76R
115  -1.74370   -2.65887   0.48691   0.91516     2.13R

R denotes an observation with a large standardized residual.
```

General Linear Model: Flux /μmols/m2/s versus Plot, Month

```
Analysis of Variance for Flux /um, using Adjusted SS for Tests

Source       DF     Seq SS     Adj SS     Adj MS      F      P
RH Leir       1     0.0085     1.1621     1.1621   2.67  0.105
RH Maol       1     1.8341     0.8254     0.8254   1.90  0.171
RH Nam i      1     4.4700     0.0456     0.0456   0.10  0.747
RH Slet       1     2.7845     0.1020     0.1020   0.23  0.629
PAR Leir      1     1.5239     8.7394     8.7394  20.07  0.000
PAR Maol      1    20.7577     7.4624     7.4624  17.14  0.000
PAR Nam       1     1.1237     1.5772     1.5772   3.62  0.059
PAR SLet      1     6.7762     6.6161     6.6161  15.19  0.000
Air Temp      1     2.2647     0.6194     0.6194   1.42  0.235
Plot         19    12.4913    12.0055     0.6319   1.45  0.117
Month         4     2.9439     2.9439     0.7360   1.69  0.157
Error       116    50.5095    50.5095     0.4354
Total       148   107.4881

Term             Coef   SE Coef       T      P
Constant        0.036     1.177    0.03  0.976
RH Leir      -0.02604   0.01594   -1.63  0.105
```

```
RH Maol      0.01752    0.01273       1.38  0.171
RH Nam i     0.00457    0.01412       0.32  0.747
RH Slet     -0.01072    0.02214      -0.48  0.629
PAR Leir   -0.003788   0.000846      -4.48  0.000
PAR Maol   -0.002560   0.000618      -4.14  0.000
PAR Nam    -0.000935   0.000491      -1.90  0.059
PAR SLet   -0.002106   0.000540      -3.90  0.000
Air Temp     0.03343    0.02803       1.19  0.235

Unusual Observations for Flux /um

Obs  Flux /um        Fit     SE Fit  Residual   St Resid
  1  -1.90317   -0.38458    0.25357  -1.51859     -2.49R
 20   0.26120   -0.80063    0.45902   1.06183      2.24R
 61   1.42288   -0.53240    0.21832   1.95527      3.14R
 62   1.92274   -0.17937    0.26963   2.10211      3.49R
 94   1.43030   -0.27543    0.23740   1.70573      2.77R
131   0.00000   -1.12273    0.38459   1.12273      2.09R

R denotes an observation with a large standardized residual.
```

Site air temperature interaction

Model with interaction

```
Source       DF      Seq SS      Adj SS      Adj MS        F       P
Error       113     47.6670     47.6670      0.4218
```

Model without interaction

```
Source       DF      Seq SS      Adj SS      Adj MS        F       P
Error       116     50.5095     50.5095      0.4354

Combining these gives
Source       DF      Seq SS      Adj SS      Adj MS        F       P
Site.AT       3      2.8425      2.8425      0.9475     2.25  0.0864
Error       113     47.6670     47.6670      0.4218
```

Conclusion no site air temperature interaction

General Linear Model: Flux /µmols/m2/s versus Plot, Month

```
Analysis of Variance for Flux /um, using Adjusted SS for Tests

Source       DF      Seq SS      Adj SS      Adj MS        F      P
AT Leir       1      0.0001      3.7850      3.7850     9.08  0.003
AT Maol       1      7.1216      0.3877      0.3877     0.93  0.337
AT Nam i      1      1.4308      0.2489      0.2489     0.60  0.441
AT Slet       1      3.4792      0.2138      0.2138     0.51  0.475
PAR Leir      1     10.3669     11.1926     11.1926    26.86  0.000
PAR Maol      1     14.1516      5.5525      5.5525    13.32  0.000
PAR Nam       1      1.4165      1.9199      1.9199     4.61  0.034
PAR SLet      1      4.0271      4.2158      4.2158    10.12  0.002
RH            1      0.0035      0.0411      0.0411     0.10  0.754
Plot         19     14.1684     13.0748      0.6881     1.65  0.055
Month         4      2.9781      2.9781      0.7445     1.79  0.136
Error       116     48.3445     48.3445      0.4168
Total       148    107.4881

Term            Coef    SE Coef        T      P
Constant       0.067      1.081     0.06  0.951
AT Leir      0.10129    0.03361     3.01  0.003
AT Maol     -0.04959    0.05142    -0.96  0.337
AT Nam i     0.02555    0.03307     0.77  0.441
AT Slet      0.02658    0.03712     0.72  0.475
PAR Leir   -0.003990   0.000770    -5.18  0.000
PAR Maol   -0.002383   0.000653    -3.65  0.000
```

```
PAR Nam    -0.000996  0.000464    -2.15  0.034
PAR SLet   -0.001821  0.000572    -3.18  0.002
RH         -0.002943  0.009375    -0.31  0.754

Unusual Observations for Flux /um

Obs  Flux /um        Fit       SE Fit   Residual    St Resid
  1  -1.90317   -0.38008      0.23352   -1.52308      -2.53R
 20   0.26120   -0.98419      0.41404    1.24539       2.51R
 61   1.42288   -0.52125      0.20762    1.94413       3.18R
 62   1.92274   -0.01899      0.25869    1.94173       3.28R
 71  -2.38314   -1.25562      0.32379   -1.12752      -2.02R
 94   1.43030   -0.24259      0.23466    1.67288       2.78R
115  -1.74370   -2.69315      0.46975    0.94945       2.14R

R denotes an observation with a large standardized residual.
```

Site RH interaction
Model with interaction

```
Source      DF      Seq SS      Adj SS      Adj MS         F       P
Error      113     47.6670     47.6670      0.4218
```

Model without interaction

```
Source      DF      Seq SS      Adj SS      Adj MS         F       P
Error      116     48.3445     48.3445      0.4168

Combining these gives
Source      DF      Seq SS      Adj SS      Adj MS         F       P
Site.RH      3      0.6775      0.6775      0.2258     0.535   0.659
Error      113     47.6670     47.6670      0.4218
```

Conclusion no site relative humidity interaction

General Linear Model: Flux /µmols/m2/s versus Plot, Month

```
Analysis of Variance for Flux /um, using Adjusted SS for Tests

Source      DF      Seq SS      Adj SS      Adj MS         F       P
AT Leir      1      0.0001      1.4056      1.4056      3.17   0.078
AT Maol      1      7.1216      1.0358      1.0358      2.34   0.129
AT Nam i     1      1.4308      0.8560      0.8560      1.93   0.167
AT Slet      1      3.4792      0.3789      0.3789      0.85   0.357
RH Leir      1      1.8820      0.6934      0.6934      1.56   0.214
RH Maol      1      3.7948      0.0539      0.0539      0.12   0.728
RH Nam i     1      0.0151      0.0074      0.0074      0.02   0.897
RH Slet      1      0.5248      0.9438      0.9438      2.13   0.147
PAR          1     21.0073     13.0900     13.0900     29.52   0.000
Plot        19     13.0115     13.6137      0.7165      1.62   0.063
Month        4      3.7893      3.7893      0.9473      2.14   0.081
Error      116     51.4316     51.4316      0.4434
Total      148    107.4881

Term             Coef    SE Coef        T       P
Constant        0.802      1.255     0.64   0.524
AT Leir       0.07670    0.04308     1.78   0.078
AT Maol      -0.09563    0.06257    -1.53   0.129
AT Nam i      0.06007    0.04323     1.39   0.167
AT Slet      -0.05241    0.05670    -0.92   0.357
RH Leir       0.02148    0.01718     1.25   0.214
RH Maol      -0.00651    0.01868    -0.35   0.728
RH Nam i      0.00253    0.01957     0.13   0.897
RH Slet      -0.04988    0.03419    -1.46   0.147
PAR         -0.001762   0.000324    -5.43   0.000

Unusual Observations for Flux /um
```

```
Obs  Flux /um       Fit      SE Fit  Residual   St Resid
  1  -1.90317  -0.33321    0.25791  -1.56996     -2.56R
  6  -0.23649  -1.32960    0.45384   1.09311      2.24R
 20   0.26120  -0.76421    0.46107   1.02541      2.13R
 61   1.42288  -0.40794    0.20976   1.83082      2.90R
 62   1.92274  -0.10946    0.24833   2.03221      3.29R
 71  -2.38314  -0.97836    0.32926  -1.40478     -2.43R
 94   1.43030  -0.28889    0.24434   1.71919      2.78R

R denotes an observation with a large standardized residual.
```

Site PAR interaction

Model with interaction

```
Source     DF     Seq SS     Adj SS      Adj MS         F      P
Error     113    47.6670    47.6670      0.4218
```

Model without interaction

```
Source     DF     Seq SS     Adj SS      Adj MS         F      P
Error     116    51.4316    51.4316      0.4434
```

```
Combining these gives
Source     DF     Seq SS     Adj SS      Adj MS         F      P
Site.RH     3     3.7646     3.7646      1.2549      2.98   0.0345
Error     113    47.6670    47.6670      0.4218
```

Conclusion site PAR interaction

Site Model then with PAR interaction but no air temp or RH

General Linear Model: Flux /µmols/m2/s versus Plot, Month

```
Analysis of Variance for Flux /um, using Adjusted SS for Tests

Source     DF     Seq SS     Adj SS      Adj MS        F      P
PAR Leir    1     2.2520     7.6615      7.6615    17.21  0.000
PAR Maol    1    21.0026    15.3399     15.3399    34.47  0.000
PAR Nam     1     0.1233     3.8783      3.8783     8.71  0.004
PAR SLet    1    12.3461     9.2277      9.2277    20.73  0.000
Air Temp    1     4.2412     1.6520      1.6520     3.71  0.056
RH          1     0.0210     0.0443      0.0443     0.10  0.753
Plot       19    11.1087    10.4997      0.5526     1.24  0.237
Month       4     3.4284     3.4284      0.8571     1.93  0.111
Error     119    52.9649    52.9649      0.4451
Total     148   107.4881

Term            Coef   SE Coef        T      P
Constant      -0.850     1.060    -0.80  0.424
PAR Leir   -0.002689  0.000648    -4.15  0.000
PAR Maol   -0.003163  0.000539    -5.87  0.000
PAR Nam    -0.001131  0.000383    -2.95  0.004
PAR SLet   -0.002080  0.000457    -4.55  0.000
Air Temp     0.05168   0.02683     1.93  0.056
RH          0.002966  0.009399     0.32  0.753

Unusual Observations for Flux /um

Obs  Flux /um       Fit      SE Fit  Residual   St Resid
  1  -1.90317  -0.43721    0.23711  -1.46596     -2.35R
 20   0.26120  -0.90919    0.38160   1.17039      2.14R
 61   1.42288  -0.53000    0.20965   1.95287      3.08R
 62   1.92274  -0.04749    0.26636   1.97023      3.22R
 71  -2.38314  -1.12556    0.32956  -1.25758     -2.17R
 94   1.43030  -0.30335    0.23746   1.73365      2.78R
```

```
R denotes an observation with a large standardized residual.
```

General Linear Model: Flux /µmols/m2/s versus Site, Month

```
Analysis of Variance for Flux /um, using Adjusted SS for Tests

Source       DF     Seq SS     Adj SS     Adj MS      F      P
PAR Leir      1     2.2520     8.4869     8.4869  18.30  0.000
PAR Maol      1    21.0026    19.7029    19.7029  42.48  0.000
PAR Nam       1     0.1233     3.3542     3.3542   7.23  0.008
PAR SLet      1    12.3461     9.3359     9.3359  20.13  0.000
Air Temp      1     4.2412     2.0912     2.0912   4.51  0.036
RH            1     0.0210     0.0402     0.0402   0.09  0.769
Site          3     1.2621     0.8549     0.2850   0.61  0.607
Month         4     3.6301     3.6301     0.9075   1.96  0.105
Error       135    62.6097    62.6097     0.4638
Total       148   107.4881

Term            Coef    SE Coef        T      P
Constant      -0.907      1.010    -0.90  0.371
PAR Leir   -0.002687   0.000628    -4.28  0.000
PAR Maol   -0.003168   0.000486    -6.52  0.000
PAR Nam    -0.000989   0.000368    -2.69  0.008
PAR SLet   -0.002056   0.000458    -4.49  0.000
Air Temp     0.05505    0.02593     2.12  0.036
RH          0.002626   0.008916     0.29  0.769

Unusual Observations for Flux /um

Obs  Flux /um       Fit     SE Fit  Residual   St Resid
  1  -1.90317  -0.35686    0.21541  -1.54631     -2.39R
  3  -0.85818  -0.77401    0.36317  -0.08417     -0.15 X
  6  -0.23649  -0.94336    0.39916   0.70687      1.28 X
 18  -1.55326  -2.13478    0.41631   0.58152      1.08 X
 61   1.42288  -0.46459    0.18601   1.88747      2.88R
 62   1.92274   0.10904    0.22921   1.81370      2.83R
 71  -2.38314  -0.81670    0.17461  -1.56645     -2.38R
 73  -3.28684  -1.58358    0.29241  -1.70326     -2.77R
 94   1.43030  -0.31168    0.20839   1.74197      2.69R

R denotes an observation with a large standardized residual.
X denotes an observation whose X value gives it large influence.
```

Site test

Model with plot

```
Source       DF     Seq SS     Adj SS     Adj MS          F        P
Error       119    52.9649    52.9649     0.4451
```

Model with Site

```
Source       DF     Seq SS     Adj SS     Adj MS          F        P
Error       135    62.6097    62.6097     0.4638
```

Combining these gives

```
Source       DF     Seq SS     Adj SS     Adj MS          F        P
Site          3     1.2621     0.8549     0.2850      0.473    0.705
Plot(site)   16     9.6448     9.6448     0.6028
-----------------------------------------------------------------------
Plot         19    10.9069    10.4997     0.5526       1.24   0.2379
```

Other effects

```
Residual    119    52.9649    52.9649     0.4451
```

General Linear Model: Flux /µmols/m2/s versus Damage, Month

```
Analysis of Variance for Flux /um, using Adjusted SS for Tests

Source      DF      Seq SS     Adj SS      Adj MS       F      P
PAR Leir     1      2.2520    14.2989     14.2989   31.01  0.000
PAR Maol     1     21.0026    25.6811     25.6811   55.70  0.000
PAR Nam      1      0.1233     3.3461      3.3461    7.26  0.008
PAR SLet     1     12.3461    16.2864     16.2864   35.32  0.000
Air Temp     1      4.2412     1.9470      1.9470    4.22  0.042
RH           1      0.0210     0.0673      0.0673    0.15  0.703
Damage       1      0.2018     0.3009      0.3009    0.65  0.421
Month        4      4.1365     4.1365      1.0341    2.24  0.068
Error      137     63.1637    63.1637      0.4610
Total      148    107.4881

Term             Coef    SE Coef        T       P
Constant       -0.982      1.001    -0.98   0.328
PAR Leir    -0.002600   0.000467    -5.57   0.000
PAR Maol    -0.002875   0.000385    -7.46   0.000
PAR Nam     -0.000980   0.000364    -2.69   0.008
PAR SLet    -0.002309   0.000389    -5.94   0.000
Air Temp      0.05294    0.02576     2.05   0.042
RH           0.003337   0.008732     0.38   0.703

Unusual Observations for Flux /um

Obs  Flux /um       Fit      SE Fit  Residual    St Resid
  1  -1.90317  -0.32898     0.21327  -1.57419      -2.44R
  3  -0.85818  -0.76312     0.36105  -0.09506      -0.17 X
  6  -0.23649  -0.94751     0.39796   0.71102       1.29 X
 18  -1.55326  -2.31907     0.37445   0.76581       1.35 X
 61   1.42288  -0.47350     0.18527   1.89638       2.90R
 62   1.92274  -0.00795     0.18563   1.93069       2.96R
 71  -2.38314  -0.80490     0.17308  -1.57824      -2.40R
 73  -3.28684  -1.57274     0.27247  -1.71409      -2.76R
 94   1.43030  -0.18058     0.16155   1.61088       2.44R

R denotes an observation with a large standardized residual.
X denotes an observation whose X value gives it large influence.
```

Site test

Model with plot

```
Source      DF      Seq SS     Adj SS      Adj MS         F      P
Error      119     52.9649    52.9649      0.4451
```

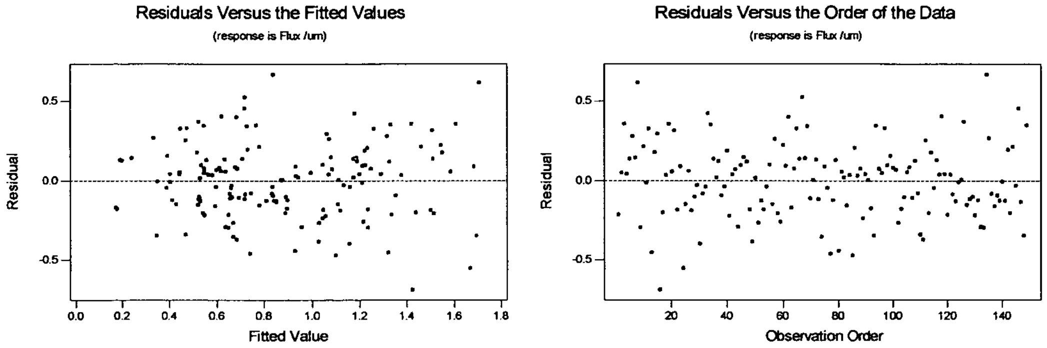
Model with Site

```
Source      DF      Seq SS     Adj SS      Adj MS         F      P
Error      137     63.1637    63.1637      0.4610
```

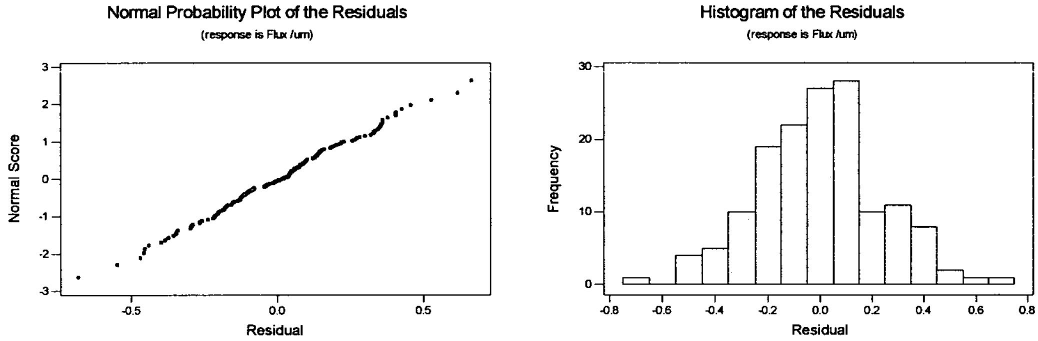
Combining these gives

```
Source      DF      Seq SS     Adj SS      Adj MS         F      P
Damage       1      0.2018     0.3009      0.3009     0.531  0.4756
Plot(Dama)  18     10.1988    10.1988      0.5666
```

8.4.1e Main sites 2005 CO_2 Dark Flux



Main sites 2005 CO_2 dark residuals



CH5 App Figure 6: Residual plots for Main sites 2005 CO_2 Dark Flux

General Linear Model: Flux /µmols/m2/s versus Plot, Month

```
Analysis of Variance for Flux /um, using Adjusted SS for Tests

Source      DF     Seq SS     Adj SS     Adj MS      F      P
ST Leir      1    0.12096    0.98636    0.98636  14.44  0.000
ST Maol      1    1.02939    0.14725    0.14725   2.16  0.145
ST Nam i     1    1.31362    2.24872    2.24872  32.92  0.000
ST Slet      1   10.92405    2.09269    2.09269  30.63  0.000
Plot        19    4.67353    4.55036    0.23949   3.51  0.000
Month        4    2.50871    2.50871    0.62718   9.18  0.000
Error      121    8.26605    8.26605    0.06831
Total      148   28.83631

Term           Coef    SE Coef       T      P
Constant    -0.3934     0.2313   -1.70  0.092
ST Leir     0.11846    0.03117    3.80  0.000
ST Maol     0.04093    0.02788    1.47  0.145
ST Nam i    0.14141    0.02465    5.74  0.000
ST Slet     0.12732    0.02300    5.53  0.000

Unusual Observations for Flux /um

Obs  Flux /um       Fit     SE Fit  Residual    St Resid
  8   2.32934   1.71152    0.09572   0.61782       2.54R
 16   0.73790   1.42367    0.10204  -0.68577      -2.85R
 24   1.11944   1.66880    0.10738  -0.54936      -2.31R
 67   1.24505   0.71712    0.12849   0.52793       2.32R
134   1.50455   0.83540    0.08627   0.66915       2.71R

R denotes an observation with a large standardized residual.
```

General Linear Model: Flux /µmols/m2/s versus Plot, Month

```
Analysis of Variance for Flux /um, using Adjusted SS for Tests

Source     DF     Seq SS     Adj SS     Adj MS      F      P
Soil Tem    1    9.54354    2.71747    2.71747  36.43  0.000
Plot       19    7.36270    7.42430    0.39075   5.24  0.000
Month       4    2.67977    2.67977    0.66994   8.98  0.000
Error     124    9.25031    9.25031    0.07460
Total     148   28.83631

Term          Coef   SE Coef      T      P
Constant   -0.5384    0.2291  -2.35  0.020
Soil Tem   0.11854   0.01964   6.04  0.000

Unusual Observations for Flux /um

Obs  Flux /um       Fit     SE Fit  Residual   St Resid
  8   2.32934   1.61380    0.07733   0.71553      2.73R
 16   0.73790   1.38734    0.07682  -0.64944     -2.48R
 30   0.75896   1.35581    0.13010  -0.59685     -2.49R
134   1.50455   0.65603    0.07530   0.84852      3.23R

R denotes an observation with a large standardized residual.
```

Site soil temperature interaction

Model with interaction

```
Source     DF     Seq SS     Adj SS     Adj MS      F      P
Error     121    8.26605    8.26605    0.06831
```

Model without interaction

```
Source     DF     Seq SS     Adj SS     Adj MS      F      P
Error     124    9.25031    9.25031    0.07460
```

Combining these gives

```
Source     DF     Seq SS     Adj SS     Adj MS      F      P
Site.ST     3    0.98426    0.98426    0.32809  4.803  0.0034
Error     121    8.26605    8.26605    0.06831
```

Conclusion site soil temperature interaction

General Linear Model: Flux /µmols/m2/s versus Site, Month

```
Analysis of Variance for Flux /um, using Adjusted SS for Tests

Source     DF     Seq SS     Adj SS     Adj MS      F      P
ST Leir     1     0.1210     0.8624     0.8624   9.68  0.002
ST Maol     1     1.0294     0.1016     0.1016   1.14  0.287
ST Nam i    1     1.3136     2.3285     2.3285  26.15  0.000
ST Slet     1    10.9241     2.0302     2.0302  22.80  0.000
Site        3     0.7212     0.6171     0.2057   2.31  0.079
Month       4     2.5278     2.5278     0.6320   7.10  0.000
Error     137    12.1993    12.1993     0.0890
Total     148    28.8363

Term          Coef   SE Coef      T      P
Constant   -0.2763    0.2548  -1.08  0.280
ST Leir    0.10805   0.03472   3.11  0.002
ST Maol    0.03350   0.03136   1.07  0.287
ST Nam i   0.14214   0.02780   5.11  0.000
ST Slet    0.12211   0.02557   4.77  0.000

Unusual Observations for Flux /um
```

```
Obs   Flux /um        Fit        SE Fit   Residual    St Resid
  8    2.32934    1.58453     0.09820    0.74481       2.64R
 16    0.73790    1.38734     0.10096   -0.64945      -2.31R
 67    1.24505    0.54566     0.07856    0.69939       2.43R
118    1.02440    0.45833     0.11371    0.56607       2.05R
134    1.50455    0.67741     0.08723    0.82714       2.90R
148    0.00000    0.72960     0.08283   -0.72960      -2.54R

R denotes an observation with a large standardized residual.
```

Model with Plot

```
Source      DF     Seq SS     Adj SS     Adj MS         F      P
Error      121    8.26605    8.26605    0.06831
```

Model with Site

```
Source      DF     Seq SS     Adj SS     Adj MS         F      P
Error      137    12.1993    12.1993     0.0890
```

Combining these gives

```
Source      DF     Seq SS     Adj SS     Adj MS         F      P
Site         3     0.7212     0.6171     0.2057     0.837   0.4932
Plot(site)  16     3.93325    3.93325    0.2458
----------------------------------------------------------------------
Plot        19    4.64535    4.55035    0.23949     3.506   <.0001
```

Other effects

```
Error      121    8.26605    8.26605    0.06831
```

General Linear Model: Flux /µmols/m2/s versus Damage, Month

```
Analysis of Variance for Flux /um, using Adjusted SS for Tests

Source      DF     Seq SS     Adj SS     Adj MS        F       P
ST Leir      1     0.1210     1.5632     1.5632    17.59   0.000
ST Maol      1     1.0294     1.0755     1.0755    12.10   0.001
ST Nam i     1     1.3136     3.6411     3.6411    40.97   0.000
ST Slet      1    10.9241     1.6635     1.6635    18.72   0.000
Damage       1     0.3169     0.4631     0.4631     5.21   0.024
Month        4     2.7780     2.7780     0.6945     7.81   0.000
Error      139    12.3533    12.3533     0.0889
Total      148    28.8363

Term           Coef    SE Coef        T       P
Constant     -0.4394    0.2430     -1.81   0.073
ST Leir      0.09847   0.02348      4.19   0.000
ST Maol      0.07631   0.02194      3.48   0.001
ST Nam i     0.15462   0.02416      6.40   0.000
ST Slet      0.09191   0.02124      4.33   0.000

Unusual Observations for Flux /um

Obs   Flux /um        Fit        SE Fit   Residual    St Resid
  8    2.32934    2.05811     0.24178    0.27123       1.56 X
 16    0.73790    1.35210     0.07818   -0.61420      -2.14R
 67    1.24505    0.58665     0.07646    0.65840       2.28R
 93    1.35549    1.57867     0.13989   -0.22318      -0.85 X
118    1.02440    0.39604     0.09170    0.62835       2.22R
134    1.50455    0.56062     0.06375    0.94393       3.24R
148    0.00000    0.76449     0.06628   -0.76449      -2.63R

R denotes an observation with a large standardized residual.
X denotes an observation whose X value gives it large influence.
```

Damage test

Model with Plot

```
Source       DF     Seq SS       Adj SS       Adj MS         F       P
Error       121    8.26605      8.26605      0.06831
```

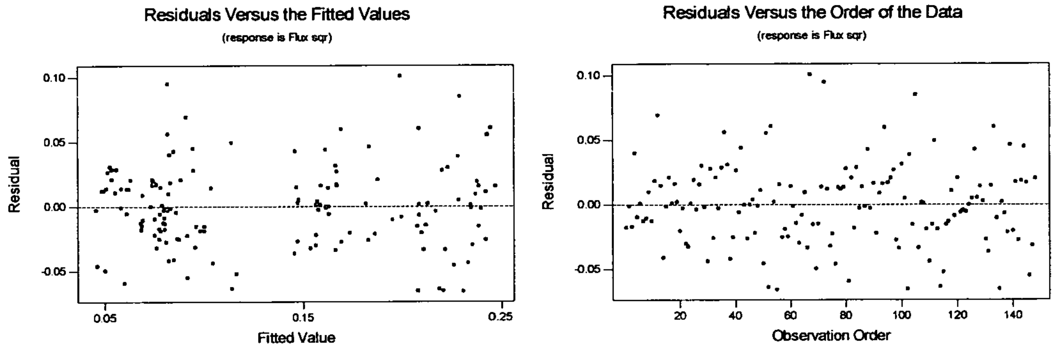
Model with Damage

```
Source       DF     Seq SS       Adj SS       Adj MS         F       P
Error       139    12.3533      12.3533      0.0889
```

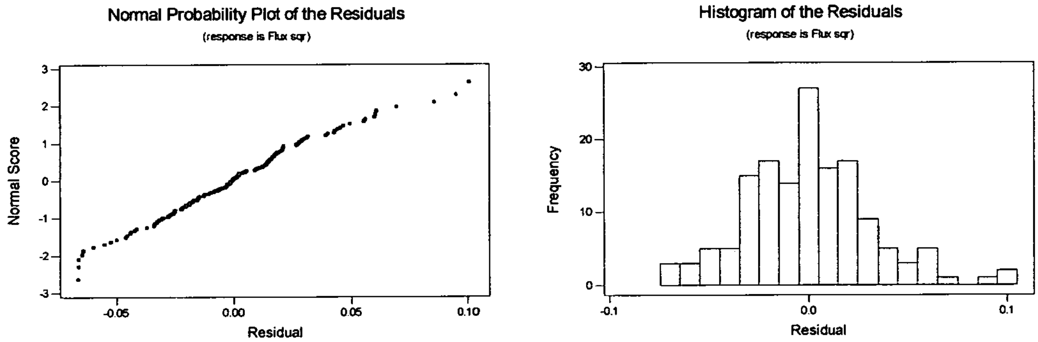
Combining these gives

```
Source       DF     Seq SS       Adj SS       Adj MS         F       P
Damage        3     0.3169       0.4631       0.4631       1.81   0.1859
Plot(Dama)  16     4.08725      4.08725      0.25545
```

8.4.1f Main sites 2005 CH_4 Flux



Main sites 2005 CH_4 residuals



CH5 App Figure 7: Residual plots for Main sites 2005 CH_4 Flux

Descriptive Statistics: Flux sqroot by Site

```
Variable    Site              N      Mean     Median    TrMean     StDev
Flux sqr    Leir             40   0.07788    0.07820   0.07708   0.03804
            Maol Don         40   0.22133    0.21633   0.22043   0.04386
            Nam Brea         36   0.07379    0.07162   0.07366   0.02403
            Sletill          32   0.16196    0.15960   0.16132   0.02724

Variable    Site        SE Mean   Minimum    Maximum        Q1        Q3
Flux sqr    Leir        0.00601   0.00000    0.17676   0.05311   0.09277
            Maol Don    0.00694   0.14264    0.31460   0.18855   0.25388
            Nam Brea    0.00400   0.00000    0.12736   0.06014   0.08069
            Sletill     0.00481   0.10843    0.22911   0.15034   0.18134
```

General Linear Model: Flux sqroot versus Plot, Month

```
Analysis of Variance for Flux sqr, using Adjusted SS for Tests

Source      DF    Seq SS    Adj SS    Adj MS      F      P
ST Leir      1  0.165826  0.000242  0.000242   0.50  0.483
ST Maol      1  0.288684  0.002469  0.002469   5.05  0.026
ST Nam i     1  0.118909  0.000350  0.000350   0.72  0.399
ST Slet      1  0.003644  0.000040  0.000040   0.08  0.774
WT Leir      1  0.008472  0.007063  0.007063  14.46  0.000
WT Maol      1  0.007147  0.000617  0.000617   1.26  0.263
WT Nam i     1  0.000679  0.000366  0.000366   0.75  0.388
WT Slet      1  0.001811  0.000985  0.000985   2.02  0.158
Plot        19  0.100235  0.094385  0.004968  10.17  0.000
Month        4  0.009149  0.009149  0.002287   4.68  0.002
Error      116  0.056671  0.056671  0.000489
Total      147  0.761227

Term           Coef   SE Coef       T      P
Constant    0.13768   0.02348    5.86  0.000
ST Leir    0.001920  0.002727    0.70  0.483
ST Maol    0.005643  0.002510    2.25  0.026
ST Nam i  -0.001793  0.002117   -0.85  0.399
ST Slet   -0.000566  0.001967   -0.29  0.774
WT Leir    0.000270  0.000071    3.80  0.000
WT Maol    0.000319  0.000284    1.12  0.263
WT Nam i   0.000207  0.000238    0.87  0.388
WT Slet    0.000280  0.000197    1.42  0.158

Unusual Observations for Flux sqr

Obs  Flux sqr       Fit     SE Fit  Residual   St Resid
 28  0.253133  0.204309   0.011573  0.048824      2.59R
 32  0.217452  0.261346   0.009413 -0.043894     -2.19R
 51  0.299000  0.249981   0.007819  0.049019      2.37R
 52  0.154498  0.206103   0.011407 -0.051605     -2.73R
 53  0.306071  0.252238   0.007714  0.053833      2.60R
 54  0.215213  0.257314   0.011376 -0.042100     -2.22R
 67  0.300428  0.242447   0.011160  0.057981      3.04R
 69  0.000000  0.046828   0.008197 -0.046828     -2.28R
 76  0.000000  0.048364   0.008243 -0.048364     -2.36R
 81  0.000000  0.063735   0.007751 -0.063735     -3.08R
105  0.314605  0.246497   0.007775  0.068108      3.29R
133  0.269186  0.221332   0.007385  0.047854      2.30R
135  0.142637  0.220768   0.007477 -0.078131     -3.76R

R denotes an observation with a large standardized residual.
```

General Linear Model: Flux sqroot versus Plot, Month

```
Analysis of Variance for Flux sqr, using Adjusted SS for Tests

Source      DF    Seq SS    Adj SS    Adj MS      F      P
ST Leir      1  0.165826  0.000245  0.000245   0.51  0.475
ST Maol      1  0.288684  0.002465  0.002465   5.17  0.025
ST Nam i     1  0.118909  0.000326  0.000326   0.68  0.410
ST Slet      1  0.003644  0.000050  0.000050   0.10  0.747
Water Ta     1  0.001138  0.007026  0.007026  14.74  0.000
Plot        19  0.116782  0.114279  0.006015  12.61  0.000
Month        4  0.009503  0.009503  0.002376   4.98  0.001
Error      119  0.056741  0.056741  0.000477
Total      147  0.761227

Term           Coef   SE Coef       T      P
Constant    0.13855   0.02102    6.59  0.000
ST Leir    0.001877  0.002618    0.72  0.475
```

```
ST Maol     0.005535  0.002434     2.27  0.025
ST Nam i   -0.001715  0.002074    -0.83  0.410
ST Slet    -0.000627  0.001935    -0.32  0.747
Water Ta    0.000267  0.000070     3.84  0.000

Unusual Observations for Flux sqr

Obs  Flux sqr       Fit      SE Fit  Residual   St Resid
 28  0.253133  0.204327    0.011343  0.048806      2.62R
 32  0.217452  0.260355    0.008141 -0.042903     -2.12R
 51  0.299000  0.250981    0.006472  0.048019      2.30R
 52  0.154498  0.206938    0.010689 -0.052439     -2.75R
 53  0.306071  0.253195    0.006462  0.052876      2.54R
 54  0.215213  0.257488    0.010930 -0.042275     -2.24R
 67  0.300428  0.241979    0.010859  0.058450      3.09R
 69  0.000000  0.046832    0.008083 -0.046832     -2.31R
 76  0.000000  0.048334    0.008140 -0.048334     -2.39R
 81  0.000000  0.064243    0.006879 -0.064243     -3.10R
105  0.314605  0.245762    0.007003  0.068843      3.33R
133  0.269186  0.221238    0.007266  0.047949      2.33R
135  0.142637  0.220684    0.007360 -0.078047     -3.80R

R denotes an observation with a large standardized residual.
```

Site water table interaction

Model with interaction

```
Source     DF     Seq SS     Adj SS     Adj MS         F      P
Error     116   0.056671   0.056671   0.000489
```

Model without interaction

```
Source     DF     Seq SS     Adj SS     Adj MS         F      P
Error     119   0.056741   0.056741   0.000477
```

Combining these gives

```
Source     DF     Seq SS     Adj SS     Adj MS         F      P
Site.WT     3   0.000070   0.000070   0.000023     0.048  0.986
Error     116   0.056671   0.056671   0.000489
```

Conclusion no site water table interaction

General Linear Model: Flux sqroot versus Plot, Month

```
Analysis of Variance for Flux sqr, using Adjusted SS for Tests

Source     DF     Seq SS     Adj SS     Adj MS       F      P
WT Slet     1   0.023514   0.001838   0.001838    3.57  0.061
WT Nam i    1   0.116722   0.000838   0.000838    1.63  0.205
WT Maol     1   0.260945   0.000430   0.000430    0.83  0.363
WT Leir     1   0.105544   0.007471   0.007471   14.49  0.000
Soil Tem    1   0.001173   0.000008   0.000008    0.02  0.898
Plot       19   0.184099   0.182818   0.009622   18.67  0.000
Month       4   0.007888   0.007888   0.001972    3.83  0.006
Error     119   0.061342   0.061342   0.000515
Total     147   0.761227

Term            Coef   SE Coef        T      P
Constant     0.15984   0.02204     7.25  0.000
WT Slet     0.000368  0.000195     1.89  0.061
WT Nam i    0.000305  0.000239     1.28  0.205
WT Maol     0.000262  0.000287     0.91  0.363
WT Leir     0.000277  0.000073     3.81  0.000
Soil Tem   -0.000215  0.001674    -0.13  0.898

Unusual Observations for Flux sqr
```

```
Obs   Flux sqr       Fit       SE Fit  Residual   St Resid
 28   0.253133  0.191911     0.011026  0.061223      3.08R
 51   0.299000  0.252257     0.007969  0.046743      2.20R
 52   0.154498  0.204927     0.011676 -0.050428     -2.59R
 53   0.306071  0.252171     0.007887  0.053900      2.53R
 67   0.300428  0.236272     0.011255  0.064156      3.25R
 69   0.000000  0.048473     0.008388 -0.048473     -2.30R
 76   0.000000  0.048301     0.008360 -0.048301     -2.29R
 81   0.000000  0.067262     0.007823 -0.067262     -3.16R
105   0.314605  0.252858     0.007508  0.061746      2.88R
135   0.142637  0.232762     0.006436 -0.090125     -4.14R

R denotes an observation with a large standardized residual.
```

Model with interaction

```
Source      DF      Seq SS      Adj SS      Adj MS         F      P
Error      116    0.056671    0.056671    0.000489
```

Model without interaction

```
Source      DF      Seq SS      Adj SS      Adj MS         F      P
Error      119    0.061342    0.061342    0.000515
```

Combining these gives

```
Source      DF      Seq SS      Adj SS      Adj MS         F      P
Site.ST      3    0.004671    0.004671    0.001557      3.18
Error      116    0.056671    0.056671    0.000489
```

Conclusion Site soil temperature interaction

Site Model is with soil interaction no water table interaction

General Linear Model: Flux sqroot versus Site, Month

```
Analysis of Variance for Flux sqr, using Adjusted SS for Tests

Source      DF      Seq SS      Adj SS      Adj MS         F      P
ST Leir      1    0.165826    0.000141    0.000141      0.12  0.731
ST Maol      1    0.288684    0.001181    0.001181      0.99  0.321
ST Nam i     1    0.118909    0.001192    0.001192      1.00  0.319
ST Slet      1    0.003644    0.001789    0.001789      1.51  0.222
Water Ta     1    0.001138    0.000375    0.000375      0.32  0.575
Site         3    0.014006    0.010529    0.003510      2.95  0.035
Month        4    0.008530    0.008530    0.002132      1.79  0.134
Error      135    0.160491    0.160491    0.001189
Total      147    0.761227

Term            Coef   SE Coef         T       P
Constant     0.14877   0.03168      4.70   0.000
ST Leir    -0.001394  0.004048     -0.34   0.731
ST Maol     0.003735  0.003747      1.00   0.321
ST Nam i   -0.003227  0.003223     -1.00   0.319
ST Slet    -0.003639  0.002966     -1.23   0.222
Water Ta    0.000030  0.000053      0.56   0.575

Unusual Observations for Flux sqr

Obs   Flux sqr       Fit       SE Fit  Residual   St Resid
 12   0.160386  0.083790     0.010113  0.076596      2.32R
 51   0.299000  0.225338     0.008278  0.073662      2.20R
 52   0.154498  0.229739     0.008877 -0.075241     -2.26R
 53   0.306071  0.226832     0.008204  0.079239      2.37R
 67   0.300428  0.221526     0.010673  0.078902      2.41R
 72   0.176756  0.071194     0.010347  0.105562      3.21R
102   0.155265  0.224223     0.009418 -0.068958     -2.08R
105   0.314605  0.222881     0.009832  0.091724      2.78R
```

```
112  0.163299  0.093520    0.010109  0.069779      2.12R
133  0.269186  0.198603    0.010352  0.070584      2.15R
144  0.139322  0.072402    0.011260  0.066920      2.05R

R denotes an observation with a large standardized residual.
```

Model with Plot

```
Source      DF      Seq SS     Adj SS     Adj MS         F      P
Error      119    0.056741   0.056741   0.000477
```

Model with Site

```
Source      DF      Seq SS     Adj SS     Adj MS         F      P
Error      135    0.160491   0.160491   0.001189

Combining these gives
Source      DF      Seq SS     Adj SS     Adj MS         F      P
Site         3    0.014006   0.010529   0.003510      0.54    0.6617
Plot(site)  16    0.103750   0.103750   0.006486
--------------------------------------------------------------------
Plot        19    0.117756   0.114279   0.006015     12.6    < 0.001
Other effects
Residual   119    0.056741   0.056741   0.000477
```

Conclusion No Site effect

Damage Effect

General Linear Model: Flux sqroot versus Damage, Month

```
Analysis of Variance for Flux sqr, using Adjusted SS for Tests

Source      DF      Seq SS     Adj SS     Adj MS         F      P
ST Leir      1    0.165826   0.008758   0.008758      7.15  0.008
ST Maol      1    0.288684   0.001809   0.001809      1.48  0.226
ST Nam i     1    0.118909   0.001441   0.001441      1.18  0.280
ST Slet      1    0.003644   0.000401   0.000401      0.33  0.568
Water Ta     1    0.001138   0.001632   0.001632      1.33  0.250
Damage       1    0.006733   0.003201   0.003201      2.61  0.108
Month        4    0.008474   0.008474   0.002119      1.73  0.147
Error      137    0.167819   0.167819   0.001225
Total      147    0.761227

Term           Coef   SE Coef        T      P
Constant    0.15006   0.03018     4.97  0.000
ST Leir   -0.008114  0.003035    -2.67  0.008
ST Maol    0.003502  0.002882     1.22  0.226
ST Nam i  -0.003542  0.003266    -1.08  0.280
ST Slet   -0.001586  0.002772    -0.57  0.568
Water Ta   0.000060  0.000052     1.15  0.250

Unusual Observations for Flux sqr

Obs  Flux sqr       Fit      SE Fit  Residual    St Resid
 12  0.160386  0.076482    0.009775  0.083905      2.50R
 51  0.299000  0.227155    0.008357  0.071845      2.11R
 52  0.154498  0.233228    0.008779 -0.078729     -2.32R
 53  0.306071  0.228556    0.008281  0.077515      2.28R
 67  0.300428  0.222757    0.010088  0.077672      2.32R
 72  0.176756  0.073007    0.010471  0.103749      3.11R
 92  0.077352  0.066234    0.017054  0.011118      0.36 X
105  0.314605  0.219764    0.007885  0.094840      2.78R
133  0.269186  0.195836    0.007887  0.073350      2.15R

R denotes an observation with a large standardized residual.
X denotes an observation whose X value gives it large influence.
```

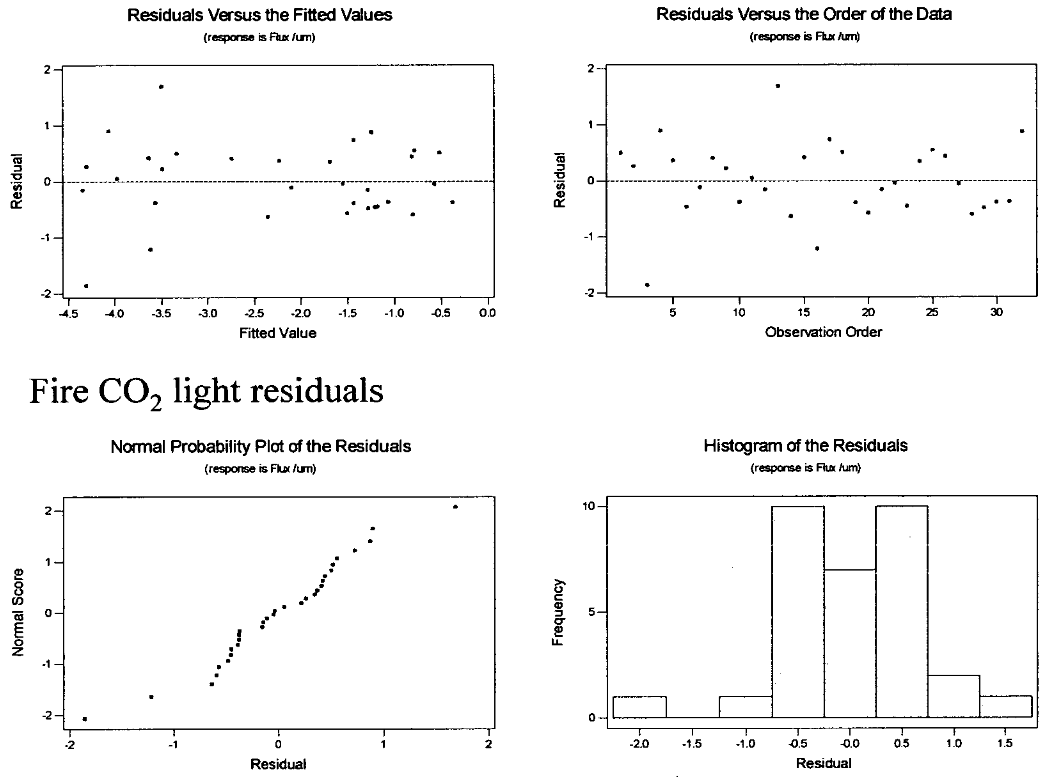
Model with Plot

```
Source      DF      Seq SS      Adj SS      Adj MS         F        P
Error      119    0.056741    0.056741    0.000477
```

Model with Damage

```
Source      DF      Seq SS      Adj SS      Adj MS         F        P
Error      137    0.167819    0.167819    0.001225

Combining these gives
Source      DF      Seq SS      Adj SS      Adj MS         F        P
Damage       1    0.006733    0.003201    0.003201      0.49    0.494
Plot(site)  16    0.103750    0.103750    0.006486
```

8.4.1g Fire sites CO2 Light Flux



Fire CO$_2$ light residuals

CH5 App Figure 8: Residual plots for Fire sites CO$_2$ Light Flux

General Linear Model: Flux /µmols/m2/s versus Plot, Month

```
Analysis of Variance for Flux /um, using Adjusted SS for Tests

Source      DF     Seq SS      Adj SS      Adj MS        F       P
AT Burn      1     0.5591      1.1114      1.1114     1.35   0.261
AT Unbur     1    13.0306      0.0033      0.0033     0.00   0.950
RH Burn      1    16.1992      1.1752      1.1752     1.43   0.248
RH Unbur     1     7.7130      0.0520      0.0520     0.06   0.805
PAR Burn     1     2.4932      1.4542      1.4542     1.77   0.201
PAR Unbu     1     0.6087      0.0039      0.0039     0.00   0.946
Plot         5     7.3733      5.0214      1.0043     1.22   0.341
Month        3     6.0480      6.0480      2.0160     2.45   0.099
Error       17    13.9739     13.9739      0.8220
Total       31    67.9991

Term           Coef    SE Coef        T       P
Constant     -32.88      30.82    -1.07   0.301
```

```
AT Burn      -1.430     1.230    -1.16  0.261
AT Unbur      0.075     1.180     0.06  0.950
RH Burn      0.5673    0.4745     1.20  0.248
RH Unbur     0.0641    0.2550     0.25  0.805
PAR Burn    0.08059   0.06059     1.33  0.201
PAR Unbu    0.00286   0.04142     0.07  0.946

Unusual Observations for Flux /um

Obs  Flux /um       Fit     SE Fit  Residual   St Resid
  3  -6.17387  -4.31361    0.52445  -1.86026     -2.52R
 13  -1.80621  -3.49696    0.49559   1.69076      2.23R

R denotes an observation with a large standardized residual.
```

General Linear Model: Flux /µmols/m2/s versus Plot, Month

```
Analysis of Variance for Flux /um, using Adjusted SS for Tests

Source      DF     Seq SS     Adj SS     Adj MS       F      P
RH Burn      1     0.2755     0.0610     0.0610    0.07  0.792
RH Unbur     1    29.6790     0.0630     0.0630    0.07  0.788
PAR Burn     1     0.0399     0.2864     0.2864    0.34  0.569
PAR Unbu     1     8.7037     0.1144     0.1144    0.13  0.718
Air temp     1     1.8972     0.2821     0.2821    0.33  0.572
Plot         5     6.8299     4.0564     0.8113    0.95  0.471
Month        3     5.2806     5.2806     1.7602    2.07  0.140
Error       18    15.2932    15.2932     0.8496
Total       31    67.9991

Term          Coef   SE Coef       T      P
Constant     -5.59     22.42   -0.25  0.806
RH Burn     0.0737    0.2753    0.27  0.792
RH Unbur    0.0706    0.2592    0.27  0.788
PAR Burn   0.02433   0.04191    0.58  0.569
PAR Unbu   0.01503   0.04096    0.37  0.718
Air temp    -0.614     1.065   -0.58  0.572

Unusual Observations for Flux /um

Obs  Flux /um       Fit     SE Fit  Residual   St Resid
  3  -6.17387  -4.18126    0.52250  -1.99261     -2.62R
  4  -3.16868  -4.17381    0.78034   1.00513      2.05R
 13  -1.80621  -3.56541    0.50085   1.75920      2.27R

R denotes an observation with a large standardized residual.
```

Site air temperature interaction

Model with interaction

```
Source      DF     Seq SS     Adj SS     Adj MS       F      P
Error       17    13.9739    13.9739     0.8220
```

Model without interaction

```
Source      DF     Seq SS     Adj SS     Adj MS       F      P
Error       18    15.2932    15.2932     0.8496
```

Combining these gives

```
Source      DF     Seq SS     Adj SS     Adj MS       F       P
Site.AT      1     1.3193     1.3193     1.3193   1.605  0.2223
Error       17    13.9739    13.9739     0.8220
```

Conclusion no interaction

General Linear Model: Flux /µmols/m2/s versus Plot, Month

```
Analysis of Variance for Flux /um, using Adjusted SS for Tests

Source      DF     Seq SS     Adj SS     Adj MS      F      P
AT Burn      1     0.5591     0.2893     0.2893   0.34  0.567
AT Unbur     1    13.0306     0.2643     0.2643   0.31  0.584
PAR Burn     1    11.2849     0.2875     0.2875   0.34  0.568
PAR Unbu     1    11.2439     0.0920     0.0920   0.11  0.746
RH           1     0.0024     0.0505     0.0505   0.06  0.810
Plot         5    11.4479     8.5254     1.7051   2.01  0.126
Month        3     5.1514     5.1514     1.7171   2.02  0.147
Error       18    15.2788    15.2788     0.8488
Total       31    67.9991

Term            Coef   SE Coef       T      P
Constant       -4.59     21.47   -0.21  0.833
AT Burn       -0.623     1.067   -0.58  0.567
AT Unbur      -0.597     1.070   -0.56  0.584
PAR Burn     0.02410   0.04142    0.58  0.568
PAR Unbu     0.01356   0.04120    0.33  0.746
RH            0.0632    0.2591    0.24  0.810

Unusual Observations for Flux /um

Obs  Flux /um        Fit      SE Fit  Residual    St Resid
  3  -6.17387   -4.15686     0.51773  -2.01700      -2.65R
  4  -3.16868   -4.17466     0.77984   1.00598       2.05R
 13  -1.80621   -3.53109     0.50286   1.72488       2.23R

R denotes an observation with a large standardized residual.
```

Site RH interaction

Model with interaction

```
Source      DF     Seq SS     Adj SS     Adj MS      F      P
Error       17    13.9739    13.9739     0.8220
```

Model without interaction

```
Source      DF     Seq SS     Adj SS     Adj MS      F      P
Error       18    15.2788    15.2788     0.8488
```

Combining these gives

```
Source      DF     Seq SS     Adj SS     Adj MS      F      P
Site.RH      1     1.3049     1.3049     1.3049   1.587    0.2248
Error       17    13.9739    13.9739     0.8220
```

Conclusion no interaction

General Linear Model: Flux /µmols/m2/s versus Plot, Month

```
Analysis of Variance for Flux /um, using Adjusted SS for Tests

Source      DF     Seq SS     Adj SS     Adj MS      F      P
AT Burn      1     0.5591     0.1707     0.1707   0.20  0.663
AT Unbur     1    13.0306     0.3241     0.3241   0.37  0.549
RH Burn      1    16.1992     0.0002     0.0002   0.00  0.989
RH Unbur     1     7.7130     0.0538     0.0538   0.06  0.806
PAR          1     1.7015     0.1256     0.1256   0.14  0.708
Plot         5     7.9072     3.7015     0.7403   0.85  0.532
Month        3     5.2207     5.2207     1.7402   2.00  0.150
Error       18    15.6677    15.6677     0.8704
Total       31    67.9991

Term            Coef   SE Coef       T      P
Constant       -1.79     22.57   -0.08  0.938
```

```
AT Burn      -0.470      1.063     -0.44  0.663
AT Unbur     -0.667      1.092     -0.61  0.549
RH Burn      0.0039     0.2743      0.01  0.989
RH Unbur     0.0653     0.2624      0.25  0.806
PAR         0.01580    0.04160      0.38  0.708

Unusual Observations for Flux /um

Obs  Flux /um       Fit      SE Fit  Residual   St Resid
  3  -6.17387  -4.14724     0.52633  -2.02663     -2.63R
  4  -3.16868  -4.17417     0.79083   1.00550      2.03R
 13  -1.80621  -3.58390     0.50616   1.77769      2.27R

R denotes an observation with a large standardized residual.
```

Site PAR interaction

Model with interaction

```
Source      DF      Seq SS      Adj SS      Adj MS         F       P
Error       17     13.9739     13.9739      0.8220
```

Model without interaction

```
Source      DF      Seq SS      Adj SS      Adj MS         F       P
Error       18     15.6677     15.6677      0.8704
```

Combining these gives

```
Source      DF      Seq SS      Adj SS      Adj MS         F       P
Site.PAR     1      1.6938      1.6938      1.6938      2.06   0.1694
Error       17     13.9739     13.9739      0.8220
```

Conclusion no interaction

General Linear Model: Flux /µmols/m2/s versus Plot, Month

```
Analysis of Variance for Flux /um, using Adjusted SS for Tests

Source      DF      Seq SS      Adj SS      Adj MS         F       P
Air temp     1      10.064       0.076       0.076      0.08   0.787
RH           1      20.425       0.115       0.115      0.11   0.739
PAR          1       1.950       0.025       0.025      0.02   0.877
Plot         5      10.888       6.265       1.253      1.24   0.329
Month        3       4.421       4.421       1.474      1.46   0.257
Error       20      20.252      20.252       1.013
Total       31      67.999

Term           Coef    SE Coef        T       P
Constant       2.59      22.70     0.11   0.910
Air temp      0.298      1.087     0.27   0.787
RH          -0.0913     0.2704    -0.34   0.739
PAR        -0.00676    0.04304    -0.16   0.877

Unusual Observations for Flux /um

Obs  Flux /um       Fit      SE Fit  Residual   St Resid
  3  -6.17387  -3.73115     0.51146  -2.44272     -2.82R
 13  -1.80621  -3.74882     0.50477   1.94261      2.23R

R denotes an observation with a large standardized residual.
```

General Linear Model: Flux /µmols/m2/s versus Site, Month

```
Analysis of Variance for Flux /um, using Adjusted SS for Tests

Source      DF      Seq SS      Adj SS      Adj MS       F       P
Air temp     1      10.064       0.273       0.273    0.26   0.616
RH           1      20.425       0.325       0.325    0.31   0.585
PAR          1       1.950       0.238       0.238    0.23   0.639
Site         1       1.956       1.127       1.127    1.07   0.312
Month        3       8.215       8.215       2.738    2.59   0.076
Error       24      25.390      25.390       1.058
Total       31      67.999

Term             Coef     SE Coef          T        P
Constant         7.71       21.14       0.36    0.719
Air temp        0.520       1.023       0.51    0.616
RH            -0.1395      0.2518      -0.55    0.585
PAR          -0.01891     0.03983      -0.47    0.639

Unusual Observations for Flux /um

Obs   Flux /um        Fit      SE Fit   Residual    St Resid
  3  -6.17387  -3.34070     0.45891   -2.83317      -3.08R

R denotes an observation with a large standardized residual.
```

Site test

Model with plot

```
Source      DF      Seq SS      Adj SS      Adj MS        F        P
Error       20      20.252      20.252       1.013
```

Model with site

```
Source      DF      Seq SS      Adj SS      Adj MS        F        P
Error       24      25.390      25.390       1.058
```

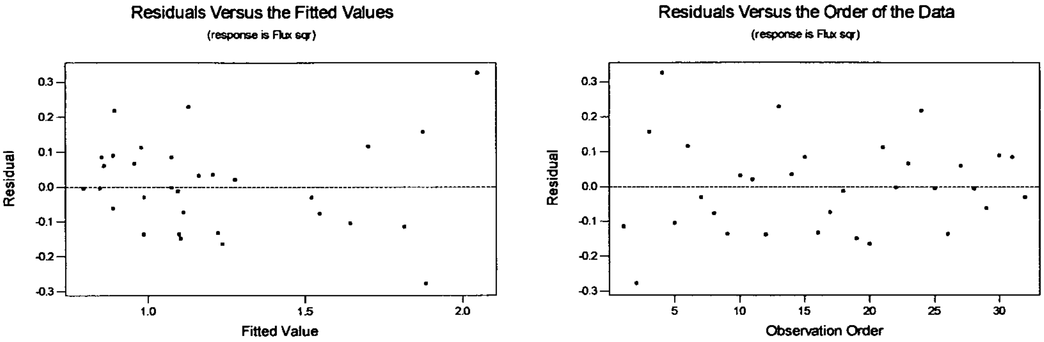
Combining these gives

```
Source      DF      Seq SS      Adj SS      Adj MS        F        P
Site        1       1.956       1.127       1.127       0.877    0.402
Plot(site)  4       5.138       5.138       1.2845
--------------------------------------------------------------------------
Plot        5        7.094      6.265       1.2530       1.24     0.3277
```

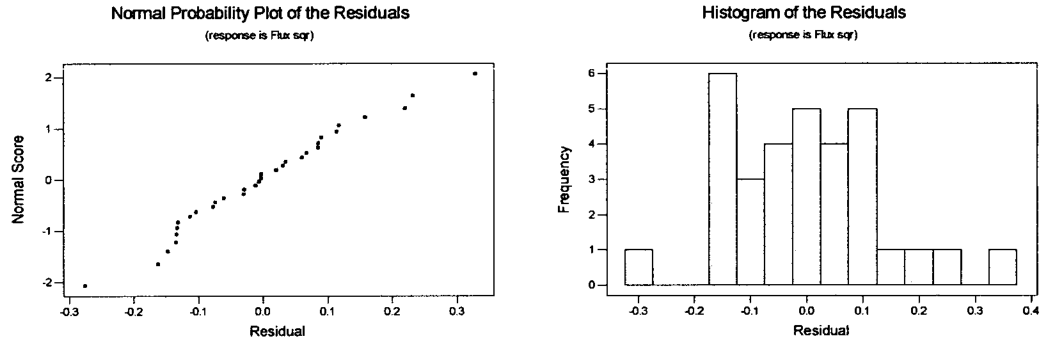
Other effects

```
Error       20      20.252      20.252       1.013
```

8.4.1h Fire sites CO_2 Dark Flux



Fire CO_2 dark residuals



CH5 App Figure 9: Residual plots for Fire sites CO_2 Dark Flux

General Linear Model: Flux sqroot versus Plot, Month

```
Analysis of Variance for Flux sqr, using Adjusted SS for Tests

Source     DF    Seq SS     Adj SS     Adj MS      F      P
ST Burn     1   0.00004    0.06790    0.06790   2.68  0.116
ST Unbur    1   3.25346    0.03141    0.03141   1.24  0.278
Plot        5   0.23449    0.15410    0.03082   1.22  0.336
Month       3   0.35063    0.35063    0.11688   4.61  0.012
Error      21   0.53188    0.53188    0.02533
Total      31   4.37049

Term           Coef    SE Coef       T      P
Constant     2.3520     0.8258    2.85  0.010
ST Burn    -0.11967    0.07309   -1.64  0.116
ST Unbur   -0.09003    0.08084   -1.11  0.278

Unusual Observations for Flux sqr

Obs  Flux sqr       Fit     SE Fit  Residual    St Resid
  2   1.60409   1.88116    0.08753  -0.27707      -2.08R
  4   2.37163   2.04459    0.10908   0.32703       2.82R

R denotes an observation with a large standardized residual.
```

General Linear Model: Flux sqroot versus Plot, Month

```
Analysis of Variance for Flux sqr, using Adjusted SS for Tests

Source     DF    Seq SS     Adj SS     Adj MS      F      P
Soil Tem    1   3.07563    0.09233    0.09233   3.55  0.073
Plot        5   0.25352    0.30449    0.06090   2.34  0.076
Month       3   0.46892    0.46892    0.15631   6.01  0.004
```

```
Error       22    0.57241    0.57241    0.02602
Total       31    4.37049

Term            Coef   SE Coef        T      P
Constant      2.7015    0.7888     3.43  0.002
Soil Tem    -0.13706   0.07276    -1.88  0.073

Unusual Observations for Flux sqr

Obs  Flux sqr        Fit     SE Fit  Residual    St Resid
  4   2.37163    2.01356    0.10772   0.35807       2.98R

R denotes an observation with a large standardized residual.
```

Model with interaction

```
Source      DF     Seq SS     Adj SS     Adj MS        F       P
Error       21    0.53188    0.53188    0.02533
```

Model without interaction

```
Source      DF     Seq SS     Adj SS     Adj MS        F       P
Error       22    0.57241    0.57241    0.02602
```

Combining these gives

```
Source      DF     Seq SS     Adj SS     Adj MS        F       P
Site.ST      1    0.04053    0.04053    0.04053      1.6  0.2198
Error       21    0.53188    0.53188    0.02533
```

Conclusion no site soil temperature interaction

General Linear Model: Flux sqroot versus Site, Month

```
Analysis of Variance for Flux sqr, using Adjusted SS for Tests

Source      DF     Seq SS     Adj SS     Adj MS       F      P
Soil Tem     1    3.07563    0.08728    0.08728    3.17  0.087
Site         1    0.11438    0.16016    0.16016    5.81  0.023
Month        3    0.46374    0.46374    0.15458    5.61  0.004
Error       26    0.71674    0.71674    0.02757
Total       31    4.37049

Term            Coef   SE Coef        T      P
Constant      2.6321    0.8006     3.29  0.003
Soil Tem    -0.13137   0.07383    -1.78  0.087

Unusual Observations for Flux sqr

Obs  Flux sqr        Fit     SE Fit  Residual    St Resid
  4   2.37163    1.89580    0.07894   0.47583       3.26R

R denotes an observation with a large standardized residual.
```

Site test

Model with plot

```
Source      DF     Seq SS     Adj SS     Adj MS        F       P
Error       22    0.57241    0.57241    0.02602
```

Model with site

```
Source      DF     Seq SS     Adj SS     Adj MS        F       P
Error       26    0.71674    0.71674    0.02757
```

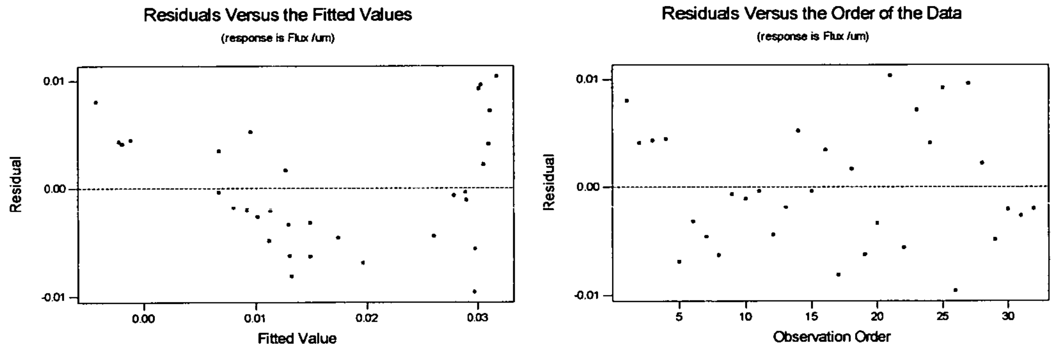
Combining these gives

```
Source      DF     Seq SS     Adj SS     Adj MS        F       P
Site         1    0.11438    0.16016    0.16016     4.44   0.1028
Plot(site)  4    0.14433    0.14433    0.03608
```

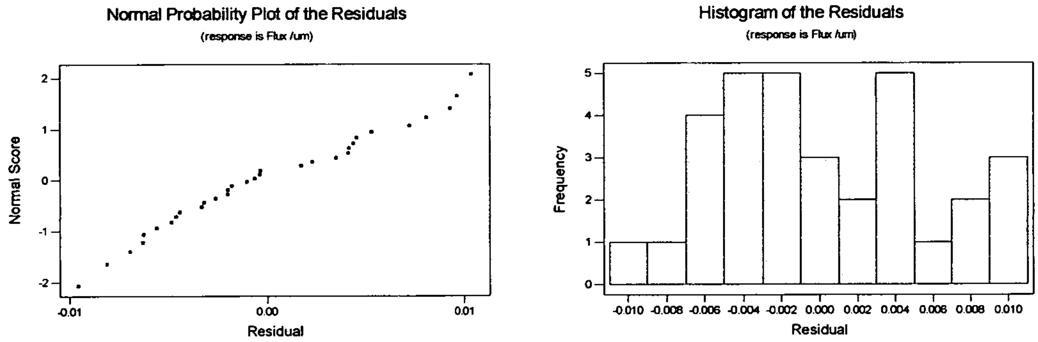
```
-----------------------------------------------------------------------------------------
Plot          5     0.25871     0.30449     0.19624      7.54   0.0003
Other effects
Error        22     0.57241     0.57241     0.02602
```

Conclusion no site effect

8.4.1i Fire sites CH_4 Flux



Fire CH_4 residuals



CH5 App Figure 10: Residual plots for Fire sites CH_4 Flux

General Linear Model: Flux /µmols/m2/s versus Plot, Month

```
Analysis of Variance for Flux /um, using Adjusted SS for Tests

Source     DF     Seq SS      Adj SS      Adj MS        F      P
ST burnt    1  0.0016470   0.0000000   0.0000000     0.00  0.974
ST Unbur    1  0.0016906   0.0000078   0.0000078     0.39  0.538
WT Burn     1  0.0001391   0.0000007   0.0000007     0.03  0.858
WT unbur    1  0.0001929   0.0000062   0.0000062     0.31  0.583
Plot        5  0.0007608   0.0005040   0.0001008     5.05  0.004
Month       3  0.0001900   0.0001900   0.0000633     3.17  0.048
Error      19  0.0003792   0.0003792   0.0000200
Total      31  0.0049997

Term            Coef    SE Coef         T      P
Constant     0.00689    0.02567      0.27  0.791
ST burnt    0.000082   0.002466      0.03  0.974
ST Unbur    0.001444   0.002304      0.63  0.538
WT Burn     0.000003   0.000018      0.18  0.858
WT unbur   -0.000022   0.000039     -0.56  0.583
```

```
Unusual Observations for Flux /um

Obs  Flux /um       Fit      SE Fit  Residual   St Resid
 26  0.020127  0.027305    0.002909 -0.007178     -2.12R

R denotes an observation with a large standardized residual.
```

General Linear Model: Flux /µmols/m2/s versus Plot, Month

```
Analysis of Variance for Flux /um, using Adjusted SS for Tests

Source     DF     Seq SS     Adj SS     Adj MS      F      P
ST burnt    1  0.0016470  0.0000036  0.0000036   0.18  0.674
ST Unbur    1  0.0016906  0.0000082  0.0000082   0.42  0.524
Water Ta    1  0.0000011  0.0000005  0.0000005   0.03  0.875
Plot        5  0.0010913  0.0010378  0.0002076  10.67  0.000
Month       3  0.0001804  0.0001804  0.0000601   3.09  0.050
Error      20  0.0003892  0.0003892  0.0000195
Total      31  0.0049997

Term           Coef   SE Coef       T      P
Constant    0.01364   0.02355    0.58  0.569
ST burnt  -0.000873  0.002042   -0.43  0.674
ST Unbur   0.001475  0.002275    0.65  0.524
Water Ta   0.000003  0.000018    0.16  0.875

Unusual Observations for Flux /um

Obs  Flux /um       Fit      SE Fit  Residual   St Resid
 26  0.020127  0.027654    0.002831 -0.007527     -2.22R

R denotes an observation with a large standardized residual.
```

Model with interaction

```
Source     DF     Seq SS     Adj SS     Adj MS        F      P
Error      19  0.0003792  0.0003792  0.0000200
```

Model without interaction

```
Source     DF     Seq SS     Adj SS     Adj MS        F      P
Error      20  0.0003892  0.0003892  0.0000195
```

Combining these gives

```
Source     DF     Seq SS     Adj SS     Adj MS        F      P
Site.WT     1  0.0000100  0.0000100  0.0000100      0.5   0.4881
Error      19  0.0003792  0.0003792  0.0000200
```

Conclusion no site water table interaction

General Linear Model: Flux /µmols/m2/s versus Plot, Month

```
Analysis of Variance for Flux /um, using Adjusted SS for Tests

Source     DF     Seq SS     Adj SS     Adj MS      F      P
WT Burn     1  0.0002513  0.0000022  0.0000022   0.11  0.744
WT unbur    1  0.0017159  0.0000628  0.0000628   3.18  0.090
Soil Tem    1  0.0002094  0.0000038  0.0000038   0.19  0.664
Plot        5  0.0022254  0.0020713  0.0004143  21.00  0.000
Month       3  0.0002030  0.0002030  0.0000677   3.43  0.037
Error      20  0.0003946  0.0003946  0.0000197
Total      31  0.0049997

Term           Coef   SE Coef       T      P
Constant    0.00292   0.02513    0.12  0.909
WT Burn    0.000006  0.000018    0.33  0.744
WT unbur  -0.000047  0.000026   -1.78  0.090
```

```
Soil Tem    0.000983  0.002230      0.44   0.664
```

Model with interaction

```
Source      DF      Seq SS      Adj SS      Adj MS          F        P
Error       19   0.0003792   0.0003792   0.0000200
```

Model without interaction

```
Source      DF      Seq SS      Adj SS      Adj MS          F        P
Error       20   0.0003946   0.0003946   0.0000197
```

Combining these gives

```
Source      DF      Seq SS      Adj SS      Adj MS          F        P
Site.ST      1   0.0000154   0.0000154   0.0000154       0.77   0.3912
Error       19   0.0003792   0.0003792   0.0000200
```

Conclusion no site soil temperature interaction

General Linear Model: Flux /µmols/m2/s versus Plot, Month

```
Analysis of Variance for Flux /um, using Adjusted SS for Tests

Source      DF      Seq SS      Adj SS      Adj MS       F       P
Soil Tem     1   0.0009318   0.0000247   0.0000247    0.83   0.372
Water Ta     1   0.0002446   0.0000306   0.0000306    1.03   0.321
Plot         5   0.0030675   0.0026166   0.0005233   17.68   0.000
Month        3   0.0001340   0.0001340   0.0000447    1.51   0.241
Error       21   0.0006217   0.0006217   0.0000296
Total       31   0.0049997

Term             Coef    SE Coef         T       P
Constant      0.04442    0.02689      1.65   0.113
Soil Tem    -0.002255   0.002470     -0.91   0.372
Water Ta     0.000021   0.000021      1.02   0.321
```

General Linear Model: Flux /µmols/m2/s versus Site, Month

```
Analysis of Variance for Flux /um, using Adjusted SS for Tests

Source      DF      Seq SS      Adj SS      Adj MS       F       P
Soil Tem     1   0.0009318   0.0000236   0.0000236    0.63   0.435
Water Ta     1   0.0002446   0.0000226   0.0000226    0.60   0.446
Site         1   0.0026553   0.0022980   0.0022980   61.10   0.000
Month        3   0.0002276   0.0002276   0.0000759    2.02   0.137
Error       25   0.0009403   0.0009403   0.0000376
Total       31   0.0049997

Term             Coef    SE Coef         T       P
Constant      0.03765    0.02929      1.29   0.210
Soil Tem    -0.002144   0.002704     -0.79   0.435
Water Ta    -0.000014   0.000018     -0.77   0.446
```

Model with Plot

```
Source      DF      Seq SS      Adj SS      Adj MS          F        P
Error       21   0.0006217   0.0006217   0.0000296
```

Model With Site

```
Source      DF      Seq SS      Adj SS      Adj MS          F        P
Error       25   0.0009403   0.0009403   0.0000376
```

Combining these

```
Source      DF      Seq SS      Adj SS      Adj MS          F        P
Site         1   0.0003186   0.0003186   0.0003186      10.76   0.0036
Error       21   0.0006217   0.0006217   0.0000296
```

```
----------------------------------------------------------------------------------------------------------------
Plot(site) 22  0.0009403  0.0009403  0.0000427     1.44   0.2037
Residual   21  0.0006217  0.0006217  0.0000296
```

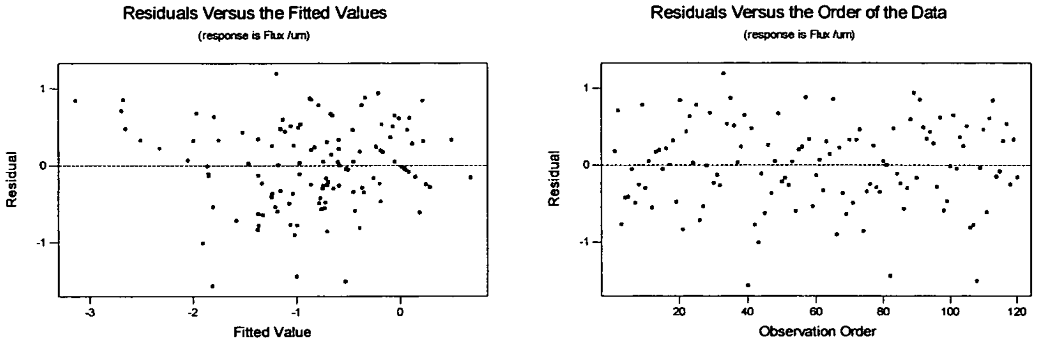
Descriptive Statistics: Flux /µmols/m2/s, Soil Temp, Water Table by Site

```
Variable   Site               N       Mean     Median     TrMean      StDev
Flux /um   Burnt             16    0.02640    0.02751    0.02656    0.01106
           Unburnt           16    0.00719    0.00656    0.00701    0.00377
Soil Tem   Burnt             16     10.814     10.210     10.666      2.801
           Unburnt           16     10.901     10.350     10.786      2.512
Water Ta   Burnt             16     -193.8     -140.0     -177.9      168.5
           Unburnt           16     -147.2      -95.0     -139.6      116.4
Variable   Site         SE Mean    Minimum    Maximum         Q1         Q3
Flux /um   Burnt        0.00277    0.00859    0.04200    0.01455    0.03747
           Unburnt      0.00094    0.00210    0.01480    0.00405    0.00953
Soil Tem   Burnt          0.700      7.900     15.800      8.348     13.731
           Unburnt        0.628      8.000     15.400      8.692     13.562
Water Ta   Burnt           42.1     -580.0      -30.0     -247.5     -102.5
           Unburnt         29.1     -380.0      -20.0     -245.0      -80.0
```

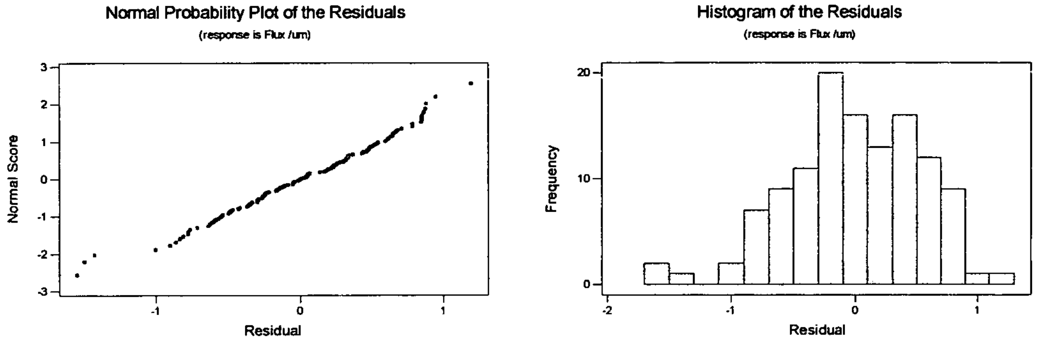
General Linear Model: Flux /µmols/m2/s versus Site, Month

```
Factor     Type Levels Values
Site      fixed      2 Burnt   Unburnt
Month     fixed      4      July    August September    October

Analysis of Variance for Flux /um, using Adjusted SS for Tests

Source     DF     Seq SS     Adj SS     Adj MS       F      P
Soil Tem    1  0.0009318  0.0000236  0.0000236    0.63  0.435
Water Ta    1  0.0002446  0.0000226  0.0000226    0.60  0.446
Site        1  0.0026553  0.0022980  0.0022980   61.10  0.000
Month       3  0.0002276  0.0002276  0.0000759    2.02  0.137
Error      25  0.0009403  0.0009403  0.0000376
Total      31  0.0049997

Term           Coef    SE Coef        T      P
Constant    0.03765    0.02929     1.29  0.210
Soil Tem  -0.002144   0.002704    -0.79  0.435
Water Ta  -0.000014   0.000018    -0.77  0.446
```

8.4.1j Drain sites CO_2 Light Flux



Drain CO_2 light residuals



CH5 App Figure 11: Residual plots for Drain 2003-4 CO_2 Light Flux

General Linear Model: Flux /µmols/m2/s versus Plot, Month

```
Analysis of Variance for Flux /um, using Adjusted SS for Tests

Source      DF     Seq SS     Adj SS     Adj MS      F      P
AT Block     1     0.3180     0.0760     0.0760   0.20  0.656
AT Centr     1     6.1665     0.1755     0.1755   0.46  0.499
AT Unblo     1    29.2228     0.0013     0.0013   0.00  0.954
RH Block     1     0.4225     0.2609     0.2609   0.69  0.410
RH Centr     1     0.9914     1.4886     1.4886   3.92  0.051
RH Unblo     1     0.2505     0.0391     0.0391   0.10  0.749
PAR Bloc     1     1.8918     1.4014     1.4014   3.69  0.058
PAR Cent     1     8.6097     9.4345     9.4345  24.82  0.000
PAR Unbl     1     2.6473     2.4926     2.4926   6.56  0.012
Plot        14     3.3106     2.9610     0.2115   0.56  0.892
Month        4     9.3690     9.3690     2.3422   6.16  0.000
Error       92    34.9666    34.9666     0.3801
Total      119    98.1667

Term            Coef    SE Coef        T      P
Constant      -1.196      1.314    -0.91  0.365
AT Block    -0.03267    0.07308    -0.45  0.656
AT Centr     0.02928    0.04309     0.68  0.499
AT Unblo    -0.00330    0.05682    -0.06  0.954
RH Block     0.01561    0.01884     0.83  0.410
RH Centr     0.02646    0.01337     1.98  0.051
RH Unblo     0.00563    0.01757     0.32  0.749
PAR Bloc   -0.002288   0.001192    -1.92  0.058
PAR Cent   -0.002373   0.000476    -4.98  0.000
PAR Unbl   -0.001990   0.000777    -2.56  0.012
```

```
Unusual Observations for Flux /um

Obs  Flux /um       Fit      SE Fit  Residual    St Resid
 33   0.00000  -1.19354     0.18203   1.19354       2.03R
 40  -3.37434  -1.80947     0.33334  -1.56487      -3.02R
 72  -2.17550  -2.50809     0.52074   0.33259       1.01 X
 82  -2.43610  -0.99904     0.20726  -1.43706      -2.48R
108  -2.03878  -0.53123     0.20678  -1.50755      -2.60R

R denotes an observation with a large standardized residual.
X denotes an observation whose X value gives it large influence.
```

General Linear Model: Flux /μmols/m2/s versus Plot, Month

```
Analysis of Variance for Flux /um, using Adjusted SS for Tests

Source     DF    Seq SS     Adj SS     Adj MS       F      P
RH Block    1    2.9853     0.5226     0.5226    1.39  0.241
RH Centr    1    0.4553     1.2693     1.2693    3.38  0.069
RH Unblo    1   19.2306     0.0945     0.0945    0.25  0.617
PAR Bloc    1    2.1661     2.9688     2.9688    7.92  0.006
PAR Cent    1   18.9945     9.6153     9.6153   25.64  0.000
PAR Unbl    1    6.1248     3.9996     3.9996   10.66  0.002
Air Temp    1    0.5551     0.0437     0.0437    0.12  0.734
Plot       14    3.2279     2.8506     0.2036    0.54  0.901
Month       4    9.1747     9.1747     2.2937    6.12  0.000
Error      94   35.2524    35.2524     0.3750
Total     119   98.1667

Term           Coef    SE Coef        T      P
Constant     -1.634      1.203    -1.36  0.178
RH Block    0.02049    0.01736     1.18  0.241
RH Centr    0.02338    0.01271     1.84  0.069
RH Unblo    0.00787    0.01567     0.50  0.617
PAR Bloc  -0.002769   0.000984    -2.81  0.006
PAR Cent  -0.002243   0.000443    -5.06  0.000
PAR Unbl  -0.002147   0.000657    -3.27  0.002
Air Temp    0.01254    0.03674     0.34  0.734

Unusual Observations for Flux /um

Obs  Flux /um       Fit      SE Fit  Residual    St Resid
 33   0.00000  -1.20443     0.18017   1.20443       2.06R
 40  -3.37434  -1.78502     0.32904  -1.58932      -3.08R
 82  -2.43610  -0.94737     0.19484  -1.48874      -2.56R
108  -2.03878  -0.48621     0.19810  -1.55258      -2.68R

R denotes an observation with a large standardized residual.
```

Site air temperature interaction

Model with interaction

```
Source     DF    Seq SS     Adj SS     Adj MS        F       P
Error      92   34.9666    34.9666     0.3801
```

Model without interaction

```
Source     DF    Seq SS     Adj SS     Adj MS        F       P
Error      94   35.2524    35.2524     0.3750
```

Combining these gives

```
Source     DF    Seq SS     Adj SS     Adj MS        F       P
Site.AT     2    0.2858     0.2858     0.1429    0.376  0.6877
Error      92   34.9666    34.9666     0.3801
```

Conclusion no interaction

General Linear Model: Flux /µmols/m2/s versus Plot, Month

```
Analysis of Variance for Flux /um, using Adjusted SS for Tests

Source      DF     Seq SS     Adj SS     Adj MS      F      P
AT Block     1     0.3180     0.0581     0.0581   0.15  0.695
AT Centr     1     6.1665     0.0949     0.0949   0.25  0.616
AT Unblo     1    29.2228     0.0442     0.0442   0.12  0.732
PAR Bloc     1     2.3120     1.4440     1.4440   3.84  0.053
PAR Cent     1     9.4571    10.0615    10.0615  26.78  0.000
PAR Unbl     1     2.4518     2.9374     2.9374   7.82  0.006
RH           1     0.4914     1.3761     1.3761   3.66  0.059
Plot        14     2.9798     2.9862     0.2133   0.57  0.884
Month        4     9.4448     9.4448     2.3612   6.28  0.000
Error       94    35.3226    35.3226     0.3758
Total      119    98.1667

Term           Coef    SE Coef       T      P
Constant     -1.681      1.151   -1.46  0.148
AT Block   -0.02654    0.06749   -0.39  0.695
AT Centr    0.02110    0.04198    0.50  0.616
AT Unblo    0.01769    0.05158    0.34  0.732
PAR Bloc  -0.002291   0.001169   -1.96  0.053
PAR Cent  -0.002426   0.000469   -5.17  0.000
PAR Unbl  -0.002124   0.000760   -2.80  0.006
RH         0.018104   0.009460    1.91  0.059

Unusual Observations for Flux /um

Obs   Flux /um        Fit     SE Fit   Residual    St Resid
 33    0.00000   -1.18926    0.18092    1.18926       2.03R
 40   -3.37434   -1.80567    0.32511   -1.56867      -3.02R
 72   -2.17550   -2.50957    0.51763    0.33407       1.02 X
 82   -2.43610   -0.99339    0.20588   -1.44271      -2.50R
108   -2.03878   -0.46232    0.18967   -1.57647      -2.70R

R denotes an observation with a large standardized residual.
X denotes an observation whose X value gives it large influence.
```

Site RH interaction

Model with interaction

```
Source      DF     Seq SS     Adj SS     Adj MS       F       P
Error       92    34.9666    34.9666     0.3801
```

Model without interaction

```
Source      DF     Seq SS     Adj SS     Adj MS       F       P
Error       94    35.3226    35.3226     0.3758
```

Combining these gives

```
Source      DF     Seq SS     Adj SS     Adj MS       F       P
Site.RH      2     0.356      0.356      0.178      0.468   0.6277
Error       92    34.9666    34.9666     0.3801
```

Conclusion no interaction

General Linear Model: Flux /µmols/m2/s versus Plot, Month

```
Analysis of Variance for Flux /um, using Adjusted SS for Tests

Source      DF     Seq SS     Adj SS     Adj MS      F      P
AT Block     1     0.3180     0.0974     0.0974   0.26  0.611
AT Centr     1     6.1665     0.1424     0.1424   0.38  0.538
AT Unblo     1    29.2228     0.0207     0.0207   0.06  0.814
RH Block     1     0.4225     0.2824     0.2824   0.76  0.386
RH Centr     1     0.9914     1.5217     1.5217   4.08  0.046
```

```
RH Unblo      1      0.2505      0.0619      0.0619    0.17   0.685
PAR           1     13.0613     11.4762     11.4762   30.78   0.000
Plot         14      3.2041      3.0127      0.2152    0.58   0.877
Month         4      9.4868      9.4868      2.3717    6.36   0.000
Error        94     35.0429     35.0429      0.3728
Total       119     98.1667

Term             Coef    SE Coef         T        P
Constant       -1.305      1.277     -1.02    0.310
AT Block     -0.03124    0.06112     -0.51    0.611
AT Centr      0.02568    0.04156      0.62    0.538
AT Unblo      0.01097    0.04655      0.24    0.814
RH Block      0.01583    0.01819      0.87    0.386
RH Centr      0.02673    0.01323      2.02    0.046
RH Unblo      0.00698    0.01713      0.41    0.685
PAR         -0.002283   0.000412     -5.55    0.000

Unusual Observations for Flux /um

Obs   Flux /um        Fit       SE Fit   Residual    St Resid
 33    0.00000   -1.20616     0.17790    1.20616       2.07R
 40   -3.37434   -1.80996     0.32079   -1.56438      -3.01R
 82   -2.43610   -0.97744     0.19902   -1.45867      -2.53R
108   -2.03878   -0.53048     0.20478   -1.50830      -2.62R

R denotes an observation with a large standardized residual.
```

Site PAR interaction

Model with interaction

```
Source      DF     Seq SS     Adj SS      Adj MS        F       P
Error       92    34.9666    34.9666      0.3801
```

Model without interaction

```
Source      DF     Seq SS     Adj SS      Adj MS        F       P
Error       94    35.0429    35.0429      0.3728
```

Combining these gives

```
Source      DF     Seq SS     Adj SS      Adj MS        F       P
Site.PAR     2     0.0763     0.0763      0.03815     0.1     0.9049
Error       92    34.9666    34.9666      0.3801
```

Conclusion no interaction

General Linear Model: Flux /µmols/m2/s versus Plot, Month

```
Analysis of Variance for Flux /um, using Adjusted SS for Tests

Source      DF     Seq SS     Adj SS      Adj MS        F       P
Air Temp     1    34.3949     0.0712      0.0712     0.19   0.660
RH           1     0.9358     1.8477      1.8477     5.06   0.027
PAR          1    14.1566    12.7370     12.7370    34.85   0.000
Plot        14     3.4280     3.2010      0.2286     0.63   0.838
Month        4     9.4386     9.4386      2.3596     6.46   0.000
Error       98    35.8129    35.8129      0.3654
Total      119    98.1667

Term             Coef    SE Coef         T        P
Constant       -2.057      1.076     -1.91    0.059
Air Temp      0.01569    0.03555      0.44    0.660
RH           0.020292   0.009024      2.25    0.027
PAR         -0.002328   0.000394     -5.90    0.000

Unusual Observations for Flux /um

Obs   Flux /um        Fit       SE Fit   Residual    St Resid
```

```
 33   0.00000  -1.19637     0.17585   1.19637      2.07R
 40  -3.37434  -1.70771     0.29823  -1.66663     -3.17R
 82  -2.43610  -0.95770     0.18981  -1.47841     -2.58R
108  -2.03878  -0.45970     0.18499  -1.57908     -2.74R

R denotes an observation with a large standardized residual.
```

General Linear Model: Flux /µmols/m2/s versus Site, Month

```
Analysis of Variance for Flux /um, using Adjusted SS for Tests

Source     DF     Seq SS     Adj SS     Adj MS       F      P
Air Temp    1    34.3949     0.0580     0.0580    0.16  0.686
RH          1     0.9358     1.8244     1.8244    5.17  0.025
PAR         1    14.1566    12.7644    12.7644   36.19  0.000
Site        2     0.4437     0.2110     0.1055    0.30  0.742
Month       4     9.4329     9.4329     2.3582    6.69  0.000
Error     110    38.8029    38.8029     0.3528
Total     119    98.1667

Term            Coef   SE Coef       T      P
Constant      -2.047     1.036   -1.98  0.051
Air Temp     0.01392   0.03432    0.41  0.686
RH          0.019777  0.008696    2.27  0.025
PAR        -0.002282  0.000379   -6.02  0.000

Unusual Observations for Flux /um

Obs  Flux /um       Fit     SE Fit  Residual    St Resid
 40  -3.37434  -1.46793    0.14761  -1.90641     -3.31R
 82  -2.43610  -0.85770    0.16297  -1.57840     -2.76R
108  -2.03878  -0.35972    0.15457  -1.67906     -2.93R

R denotes an observation with a large standardized residual.
```

Model with plot

```
Source     DF     Seq SS     Adj SS     Adj MS       F      P
Error      98    35.8129    35.8129     0.3654
```

Model with site

```
Source     DF     Seq SS     Adj SS     Adj MS       F      P
Error     110    38.8029    38.8029     0.3528
```

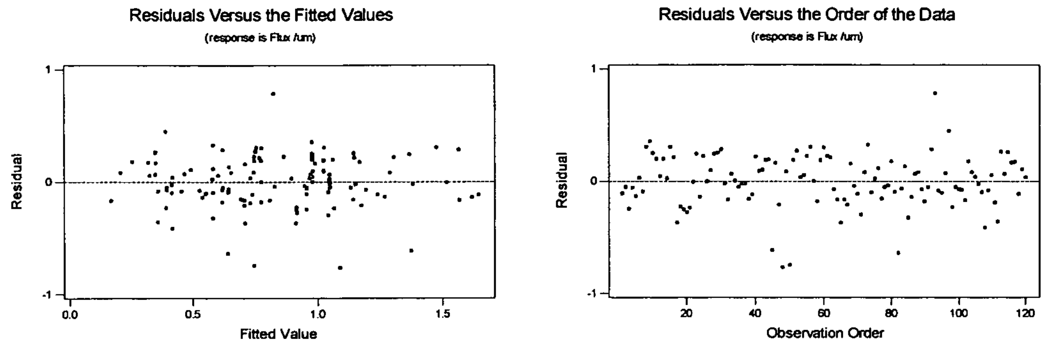
Combining these gives

```
Source       DF     Seq SS     Adj SS     Adj MS       F      P
Site          2     0.4437     0.2110     0.1055   0.423  0.6645
Plot(site)   12     2.99       2.99       0.2492
-----------------------------------------------------------------
Plot         14     3.4337     3.2010     0.2286   0.626  0.2596
```

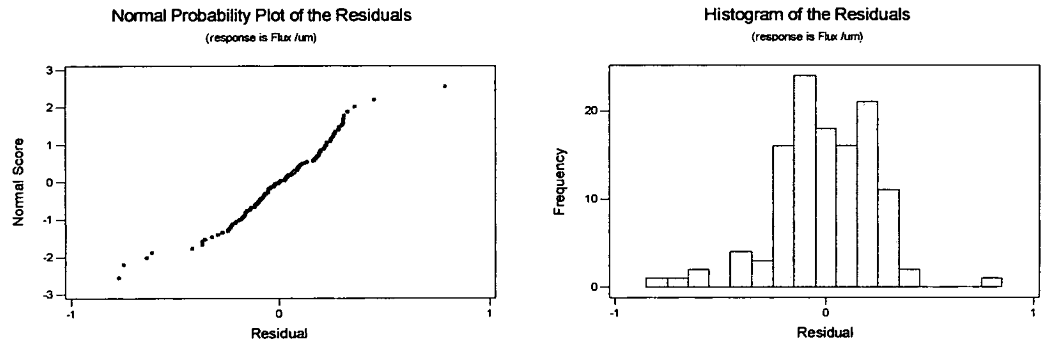
Other effects

```
Residual     98    35.8129    35.8129     0.3654
```

8.4.1k Drain sites CO_2 Dark Flux



Drains CO_2 dark residuals



CH5 App Figure 12: Residual plots for Drain CO_2 Dark Flux

General Linear Model: Flux /µmols/m2/s versus Plot, Month

```
Analysis of Variance for Flux /um, using Adjusted SS for Tests

Source      DF     Seq SS     Adj SS     Adj MS      F      P
ST Block     1    1.40464    0.18066    0.18066   2.74  0.101
ST Centr     1    0.00888    0.00025    0.00025   0.00  0.951
ST Unblo     1    7.39199    0.08938    0.08938   1.36  0.247
Plot        14    2.65190    2.49550    0.17825   2.70  0.002
Month        4    1.39377    1.39377    0.34844   5.28  0.001
Error       98    6.46172    6.46172    0.06594
Total      119   19.31290

Term            Coef   SE Coef       T      P
Constant      0.3524    0.3895    0.90  0.368
ST Block     0.06635   0.04009    1.66  0.101
ST Centr     0.00245   0.04019    0.06  0.951
ST Unblo     0.04772   0.04099    1.16  0.247

Unusual Observations for Flux /um

Obs  Flux /um        Fit     SE Fit  Residual    St Resid
 45   0.75963    1.37184    0.13823  -0.61221      -2.83R
 48   0.31899    1.08663    0.13014  -0.76764      -3.47R
 50   0.00000    0.74461    0.08900  -0.74461      -3.09R
 82   0.00000    0.63758    0.08635  -0.63758      -2.64R
 93   1.60754    0.82163    0.12570   0.78591       3.51R

R denotes an observation with a large standardized residual.
```

General Linear Model: Flux /µmols/m2/s versus Plot, Month

```
Analysis of Variance for Flux /um, using Adjusted SS for Tests

Source      DF     Seq SS     Adj SS     Adj MS       F      P
Soil Tem     1    7.71778    0.09482    0.09482    1.42  0.236
Plot        14    3.60963    3.51200    0.25086    3.76  0.000
Month        4    1.32096    1.32096    0.33024    4.96  0.001
Error      100    6.66453    6.66453    0.06665
Total      119   19.31290

Term            Coef   SE Coef        T      P
Constant      0.4213    0.3891     1.08  0.281
Soil Tem     0.04021   0.03371     1.19  0.236

Unusual Observations for Flux /um

Obs  Flux /um        Fit     SE Fit   Residual    St Resid
 45   0.75963    1.34408    0.12729   -0.58446      -2.60R
 48   0.31899    1.03417    0.12473   -0.71519      -3.16R
 50   0.00000    0.69877    0.08534   -0.69877      -2.87R
 82   0.00000    0.58221    0.08036   -0.58221      -2.37R
 93   1.60754    0.82746    0.12500    0.78009       3.45R
 97   0.83685    0.32611    0.07455    0.51075       2.07R

R denotes an observation with a large standardized residual.
```

Site soil temperature interaction

Model with interaction

```
Source      DF     Seq SS     Adj SS     Adj MS       F      P
Error       98    6.46172    6.46172    0.06594
```

Model without interaction

```
Source      DF     Seq SS     Adj SS     Adj MS       F      P
Error      100    6.66453    6.66453    0.06665
```

Combining these gives

```
Source      DF     Seq SS     Adj SS     Adj MS         F       P
Site.ST      2    0.20281    0.20281    0.101405    1.54   0.2195
Error       98    6.46172    6.46172    0.06594
```

Conclusion no site soil temperature interaction

General Linear Model: Flux /µmols/m2/s versus Site, Month

```
Analysis of Variance for Flux /um, using Adjusted SS for Tests

Source      DF     Seq SS     Adj SS     Adj MS       F      P
Soil Tem     1     7.7178     0.1061     0.1061    1.19  0.278
Site         2     0.2885     0.1900     0.0950    1.07  0.348
Month        4     1.3201     1.3201     0.3300    3.70  0.007
Error      112     9.9866     9.9866     0.0892
Total      119    19.3129

Term               Coef   SE Coef        T      P
Constant         0.3483    0.4426     0.79  0.433
Soil Tem        0.04197   0.03848     1.09  0.278

Unusual Observations for Flux /um

Obs  Flux /um        Fit     SE Fit   Residual    St Resid
 15   1.78002    1.07145    0.07315    0.70857       2.45R
 30   1.84840    1.21216    0.07257    0.63623       2.20R
 48   0.31899    1.09025    0.07269   -0.77126      -2.66R
 50   0.00000    0.70544    0.08724   -0.70544      -2.47R
```

```
 65   0.34013   0.92809    0.07669  -0.58796     -2.04R
 82   0.00000   0.64485    0.08086  -0.64485     -2.24R
 93   1.60754   0.59282    0.07290   1.01472      3.50R

R denotes an observation with a large standardized residual.
```

Site test

Model with plot

```
Source      DF     Seq SS     Adj SS     Adj MS       F      P
Error      100    6.66453    6.66453    0.06665
```

Model with site

```
Source      DF     Seq SS     Adj SS     Adj MS       F      P
Error      112     9.9866     9.9866     0.0892
```

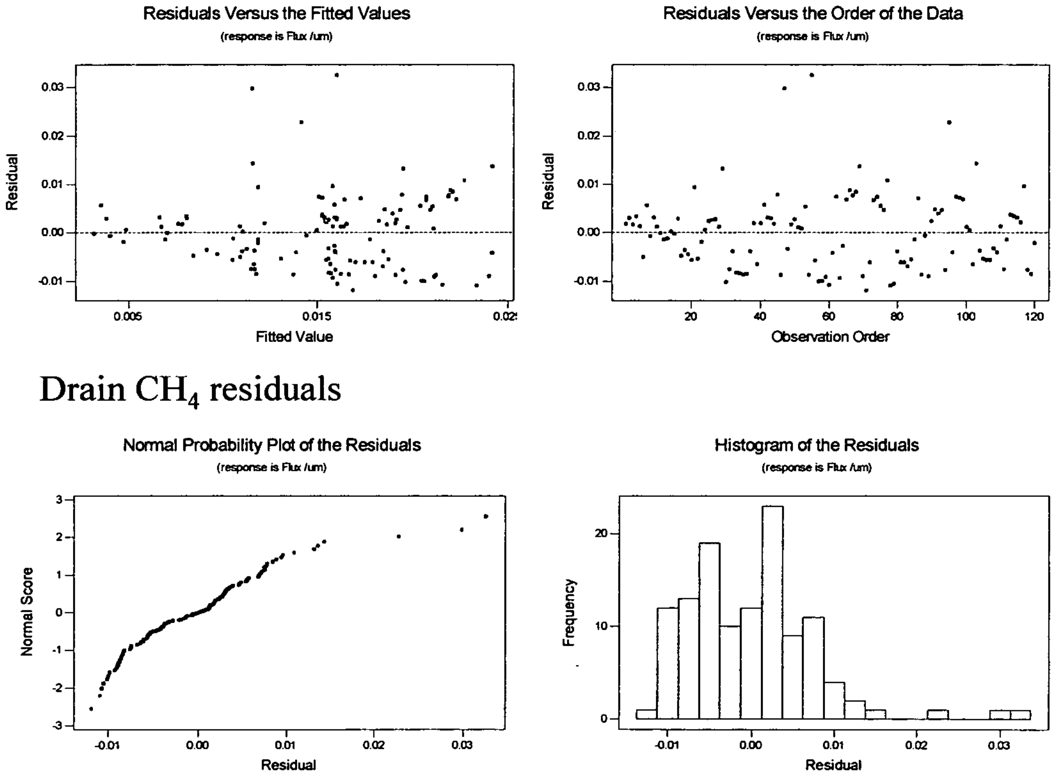
```
Combining these gives
Source      DF     Seq SS     Adj SS     Adj MS       F      P
Site         2     0.2885     0.1900     0.0950       0.34  0.7184
Plot(site)  12    3.32207    3.32207     0.2768
----------------------------------------------------------------------
Plot        14   33.61057     3.4107    0.24362      3.66   <.0001
```

Other effects

```
Error      100    6.66453    6.66453    0.06665
```

Conclusion no site effect

8.4.11 Drain sites CH_4 Flux



CH5 App Figure 13: Residual plots for Drain CH_4 Flux

General Linear Model: Flux /µmols/m2/s versus Plot, Month

```
Analysis of Variance for Flux /um, using Adjusted SS for Tests
```

```
Source      DF     Seq SS     Adj SS     Adj MS        F      P
ST Unblo     1  0.0005872  0.0001256  0.0001256     6.92  0.010
ST Centr     1  0.0000804  0.0000203  0.0000203     1.12  0.293
ST Block     1  0.0000000  0.0000197  0.0000197     1.09  0.300
Plot        14  0.0053111  0.0052485  0.0003749    20.66  0.000
Month        4  0.0021631  0.0021631  0.0005408    29.81  0.000
Error       98  0.0017779  0.0017779  0.0000181
Total      119  0.0099197

Term            Coef   SE Coef        T      P
Constant    0.003355  0.006482     0.52  0.606
ST Unblo    0.001613  0.000613     2.63  0.010
ST Centr    0.000604  0.000572     1.06  0.293
ST Block    0.000616  0.000592     1.04  0.300

Unusual Observations for Flux /um

Obs  Flux /um       Fit      SE Fit  Residual    St Resid
  7  0.009184  0.025381    0.002117 -0.016197     -4.38R
  9  0.009767  0.001120    0.001423  0.008647      2.15R
 43  0.019014  0.011393    0.003038  0.007621      2.55R
 44  0.018370  0.021028    0.003659 -0.002658     -1.22 X
 55  0.048579  0.036490    0.002021  0.012090      3.22R
 89  0.009063  0.021133    0.001302 -0.012070     -2.98R

R denotes an observation with a large standardized residual.
X denotes an observation whose X value gives it large influence.
```

General Linear Model: Flux /µmols/m2/s versus Plot, Month

```
Analysis of Variance for Flux /um, using Adjusted SS for Tests

Source      DF     Seq SS     Adj SS     Adj MS        F      P
Soil Tem     1  0.0000196  0.0000437  0.0000437     2.25  0.137
Plot        14  0.0058407  0.0057311  0.0004094    21.01  0.000
Month        4  0.0021111  0.0021111  0.0005278    27.09  0.000
Error      100  0.0019483  0.0019483  0.0000195
Total      119  0.0099197

Term            Coef   SE Coef        T      P
Constant    0.004901  0.006692     0.73  0.466
Soil Tem    0.000868  0.000579     1.50  0.137

Unusual Observations for Flux /um

Obs  Flux /um       Fit      SE Fit  Residual    St Resid
  7  0.009184  0.022683    0.001993 -0.013499     -3.43R
  9  0.009767  0.001247    0.001473  0.008520      2.05R
 20  0.004916  0.013368    0.001468 -0.008452     -2.03R
 44  0.018370  0.030623    0.001953 -0.012253     -3.10R
 47  0.041389  0.030623    0.001953  0.010766      2.72R
 55  0.048579  0.034698    0.002005  0.013881      3.53R
 89  0.009063  0.020928    0.001346 -0.011865     -2.82R

R denotes an observation with a large standardized residual.
```

Site Soil temperature interaction

Model with interaction

```
Source      DF     Seq SS     Adj SS     Adj MS        F      P
Error       98  0.0017779  0.0017779  0.0000181
```

Model without interaction

```
Source      DF     Seq SS     Adj SS     Adj MS        F      P
Error      100  0.0019483  0.0019483  0.0000195
```

Combining these gives

```
Source       DF     Seq SS      Adj SS      Adj MS        F       P
Site.ST       2  0.0001704   0.0001704   0.0000852     4.71    0.0111
Error        98  0.0017779   0.0017779   0.0000181
```

General Linear Model: Flux /µmol/m2/s versus Drain, Month

```
Analysis of Variance for Flux /um, using Adjusted SS for Tests

Source       DF     Seq SS      Adj SS      Adj MS        F       P
ST Unblo      1  0.0005872   0.0000270   0.0000270     0.42   0.517
ST Centr      1  0.0000804   0.0000691   0.0000691     1.08   0.300
ST Block      1  0.0000000   0.0001385   0.0001385     2.17   0.144
Drain         2  0.0000099   0.0000090   0.0000045     0.07   0.932
Month         4  0.0022248   0.0022248   0.0005562     8.72   0.000
Error       110  0.0070174   0.0070174   0.0000638
Total       119  0.0099197

Term           Coef    SE Coef        T       P
Constant   0.002103   0.009743     0.22   0.829
ST Unblo   0.000708   0.001088     0.65   0.517
ST Centr   0.001071   0.001029     1.04   0.300
ST Block   0.001621   0.001101     1.47   0.144

Unusual Observations for Flux /um

Obs  Flux /um        Fit       SE Fit   Residual    St Resid
 47  0.041389   0.011538     0.002429   0.029851       3.92R
 55  0.048579   0.016036     0.002166   0.032544       4.23R
 95  0.036964   0.014150     0.002458   0.022813       3.00R

R denotes an observation with a large standardized residual.
```

Model with Plot

```
Source       DF     Seq SS      Adj SS      Adj MS        F       P
Error        98  0.0017779   0.0017779   0.0000181

Model with Drain
Source       DF     Seq SS      Adj SS      Adj MS        F       P
Error       110  0.0060945   0.0060945   0.0000554

combining these gives
Source         DF     Seq SS      Adj SS      Adj MS        F       P
Drain           2  0.0000099   0.0000090   0.0000045     0.0125   0.9876
Plot(drain)12  0.0043166   0.0043166   0.0003597
--------------------------------------------------------------------------------
Plot         14  0.0043265   0.0043256   0.0003090     17.07    < 0.001
Error        98  0.0017779   0.0017779   0.0000181
```

Conclusion significant site soil temperature interaction but no drain effect

8.5 Appendices References

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