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**Assessing the impact of climate change on the Net
Ecosystem Exchange of Irish Grasslands**

A case study of CO₂ efflux using multiple microcosm
enclosure facilities

PhD Thesis

2013

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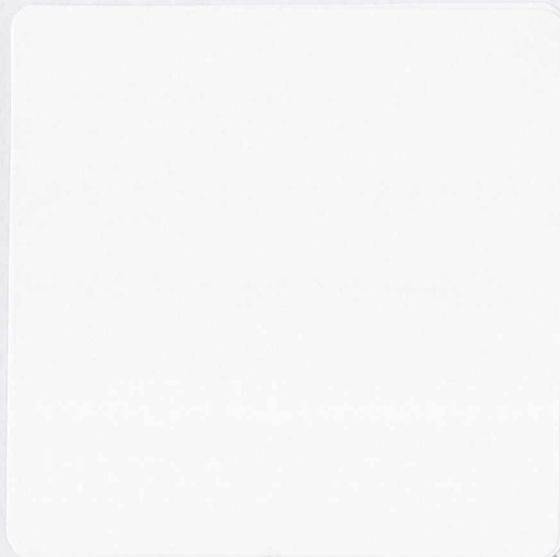
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Acknowledgements

I would like to the Prof. Mike Jones for providing me with unlimited patience, advice and expertise and also giving me the opportunity to work on this PhD thesis. I would also like to thank all the staff in the Botany Department, Trinity College Dublin and Teagasc Oak Park Research Centre, Carlow who also helped me during the course of my field work. I would like to give a special mention to Fabrizio Albanito for his help and support throughout the study.

The work of this thesis was funded by Teagasc (Irish Agricultural Research Institute) and conducted at Teagasc, Oak Park Research Centre, Carlow, Ireland.

Abstract

It is now widely accepted that human activity is having a discernible effect on the global climate, and these changes will impact upon the functioning of many of the planet's natural systems (Cox *et al.*, 2000; Trumbore, 2006). Grassland ecosystems exhibit a large interannual variability in their annual NEE (Flanagan *et al.*, 2002, Ma *et al.*, 2007) and as a consequence their role in the global C cycle remains uncertain. While GHG emissions from grasslands are intimately linked to current management practices and the ambient climate (Hopkins *et al.*, 2007; Gilmanov *et al.*, 2007), uncertainty remains how the future climate will affect the productivity of European grasslands and if under their current management regime will they become a source of CO₂ as climate change takes effect. This study aimed to quantify the impacts of two environmental variables, temperature and precipitation, on the magnitude and direction of NEE on *Lolium perenne* swards under the same management. To achieve this we proposed (a) the use of multiple microcosms to replicate both the ambient and future climate (2050) and expose swards of *L. perenne* to the two climate treatments, (b) examine the difference in NEE and assess the potential impact of environmental drivers on its components, GPP and R, and (c) investigate the potential impact climate change will have on the productivity of Irish grasslands. Our results indicated that that between both years, 2008 and 2009, net ecosystem exchange (NEE) for the *L. perenne* swards showed considerable interannual variability switching from a source to a sink of CO₂. This was primarily driven by changes in precipitation patterns and

levels, during the growing season. Our results indicate that temperature and precipitation changes to 2055 may not be detrimental to the productivity of Irish grasslands as over the two years we found for both years, the *L. perenne* swards grown within the treatment microcosms acted either as a greater sink or a smaller source of CO₂, when compared to the control swards.

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Chapter 1:

1: General introduction

1.1 Background to study

It is now widely accepted that human activity is having a discernible effect on the global climate, and that these changes will impact upon the functioning of many of the planet's natural systems (Cox *et al.*, 2000; Trumbore, 2006). Since the beginning of the industrial revolution energy demands by humans in areas such as transport, manufacturing, cement production, land use and land use change,, have lead to a dramatic increase in greenhouse gases (GHG's). For example carbon dioxide concentrations (CO₂) deemed to be the principal GHG by virtue of its higher atmospheric concentration and retention time in the atmosphere, has increased by approximately 30% to 395 ppm c. 1750. Methane, nitrous oxide and halogens are the other main GHG's and have also increased over the same period. The excess emissions of carbon dioxide and other greenhouse gases coupled with the constraints of natural ecosystems to sequester them due to land use change, has lead to an alteration of the composition of the earth's atmosphere leading to what is commonly termed "greenhouse warming". Key indicators of such changes have already been seen through departures from normal weather conditions, where studies have shown 0.7°C over the last three hundred years and of about 0.5°C during the twentieth century with the period between 1990 and 1999 was the warmest decade on record (Folland *et al.*, 2001).

If left unchecked it is expected that annual global temperatures will rise by approximately 2°C (IPCC, 2007), coupled with expected changes in precipitation levels and patterns this will inevitably impact terrestrial carbon cycles.

Agricultural land, which consists of approximately 50% of the Earth's land surface (FAOSTAT, 2006), releases significant amounts of CO₂, CH₄ and N₂O to the atmosphere via processes such as decomposition of litter and soil organic matter (SOM) (Cole *et al.*, 1997; IPCC 2001a; Paustian *et al.*, 2004). Recent studies have estimated that agriculture accounts for between 10 – 12% (5.1 to 6.1 GtCO₂ – eq. / year) of global anthropogenic emissions of greenhouse gases (GHG's). As a percentage of the global emissions of N₂O and CH₄, agriculture accounts for 60% and 50% respectively. The net flux for CO₂ emissions are estimated to be approximately balanced at approximately 0.04 GtCO₂ / yr (Smith *et al.*, 2008). However, estimating GHG fluxes from agriculture is a complex and heterogeneous process and the magnitude of emissions varies in different regions and from different management practices.

Grasslands are an important component of the global carbon budget due to the large area they occupy, their role in food production and their sink/source capacity (Suyker and Verma, 2001; Novick *et al.*, 2004; Xu & Baldocchi, 2004; Hunt *et al.*, 2002). Globally grasslands account for approximately 32% of the earth's surface and store between 10 and 30 % of global soil carbon (IPCC 2007). Attempts at quantifying different terrestrial ecosystems contribution to total carbon emissions have previously focused on forest ecosystems, which, have shown that they

are primarily sinks of carbon (Dixon *et al.*, 1994; Valentini *et al.*, 2000; De Vries *et al.*, 2000). However grasslands have been recently revisited for carbon flux studies through initiatives such as Flux- net and Carboeurope (Sousanna *et al.*, 2007; Flanagan *et al.*, 2002, Ammann *et al.*, 2007). While several short term European studies have shown this potential, the net global warming potential from GHG's exchanges with European grasslands is still not known (Batjes *et al.*, 1999; Contant *et al.*, 2001; Soussana *et al.*, 2007).

1.2 Carbon cycling in terrestrial ecosystems: an introduction to key concepts

In order for us to understand how the described changes in the climate will alter different biogeochemical cycles it is important firstly to understand how carbon moves in grassland ecosystems in an ambient climate. In general, the carbon budget of a terrestrial ecosystem is balanced by an exchange of carbon between the ecosystem and the atmosphere via photosynthesis, respiration, decomposition and combustion. More specifically carbon, usually in the form of CO₂, is fixed by plants through photosynthesis and used then in the formation of carbohydrates, which are translocated to belowground parts and in the opposite direction depending upon season and management regimes. This is termed gross primary productivity (GPP). Carbon is lost simultaneously by plant respiration (R_{auto}) and GPP minus this loss is

termed Net Primary Production (NPP). This is directly measurable through biomass. However carbon is also lost from an ecosystem via processes such as heterotrophic respiration from microbes and animals (R_{het}) and therefore the total carbon inputs GPP minus total carbon losses ($R_{auto} + R_{het}$) is termed Net Ecosystem Exchange (NEE). NEE is ecologically important as it represents the increment of carbon stored or lost by an ecosystem and its components show large temporal and seasonal variation. Where during an ecosystems' peak growing season NEE is positive as the ideal conditions for photosynthesis means that GPP exceeds respiration. In winter seasons where GPP is negligible therefore NEE is mainly negative due to heterotrophic respiration. When integrated on a larger spatial scale NEE is then commonly referred to as Net Biome Production (NBP) where the sink/source status of the ecosystem is determined after the inclusion of additional C losses such as soil erosion and dissolved organic carbon. In terms of climate change and increasing CO_2 in the atmosphere, NBP is an indication if an ecosystems is net contributor or net sink of CO_2 therefore efforts to quantify NBP across different ecosystem types is extremely

1.3 The movement and control of carbon in grasslands via net ecosystem exchange, gross primary production and respiration cycling

Grassland ecosystems are far from uniform and in general characteristics, such as NEE, nutrient dynamics, and their functions are determined by a regions present climatic and soil conditions and biota adapted to these situations (Coupland *et al.*, 1992; Scurlock *et al.*, 2002; Flanagan *et al.*, 2002; Ammann *et al.*, 2007; Soussana *et al.*, 2007). These ecosystems are also particularly complex and difficult to investigate because of the wide range of species composition, management and environmental conditions that they are exposed to. However, in general, the carbon movement in grassland occurs between the three major compartments: aboveground & and belowground biomass and the soil organic matter pool. Figure 1.1 is a schematic representation of the interaction between each pool and their regulation by climatic parameters temperature and precipitation, which are highlighted in bold (Sala, 1996).

The contributions by species of differing physiological responses to peak biomass are primarily used to classify each grassland type and the differences that occur in biomass of green shoots in various types of grassland, depend particularly on moisture regime (Sala *et al.*, 2000). While there is a uni-modal pattern of increase and decrease in green biomass in cooler regions peak biomass, which occurs early in the growing season, is dominated by C3 species that account for 75% or more of green shoot biomass (Sims *et al.*, 1978). Warmer more tropical

grasslands tend to be dominated by a similar proportion of C4 species and peak biomass usually occurs later in the growing season. Inter-annual variations in peak biomass and hence NEE, are more strongly regulated by the regions moisture regime than any other environmental variable (Knapp and Smith, 2001; Suyker *et al.*, 2003; Xu *et al.*, 2004; Jaksic *et al.*, 2006). More specifically precipitation variability has the potential to impact NEE through the meteorological and hydrological drivers of photosynthesis such as photosynthetically active radiation (PAR) and respiration rates through controls of soil moisture content. Within the carbon budget of grasslands soil respiration is the primary pathway for CO₂ fixed by plants to be returned to the atmosphere (Bauer *et al.*, 2008; Högberg and Read, 2006). Temperature exerts a strong influence on the soil respiration rate (R_h and R_a) (Raich *et al.*, 2000; Boone *et al.*, 1998; Kirschbaum, 2004; Luo *et al.*, 2006) and as a consequence most simulation models of carbon cycles use a fixed

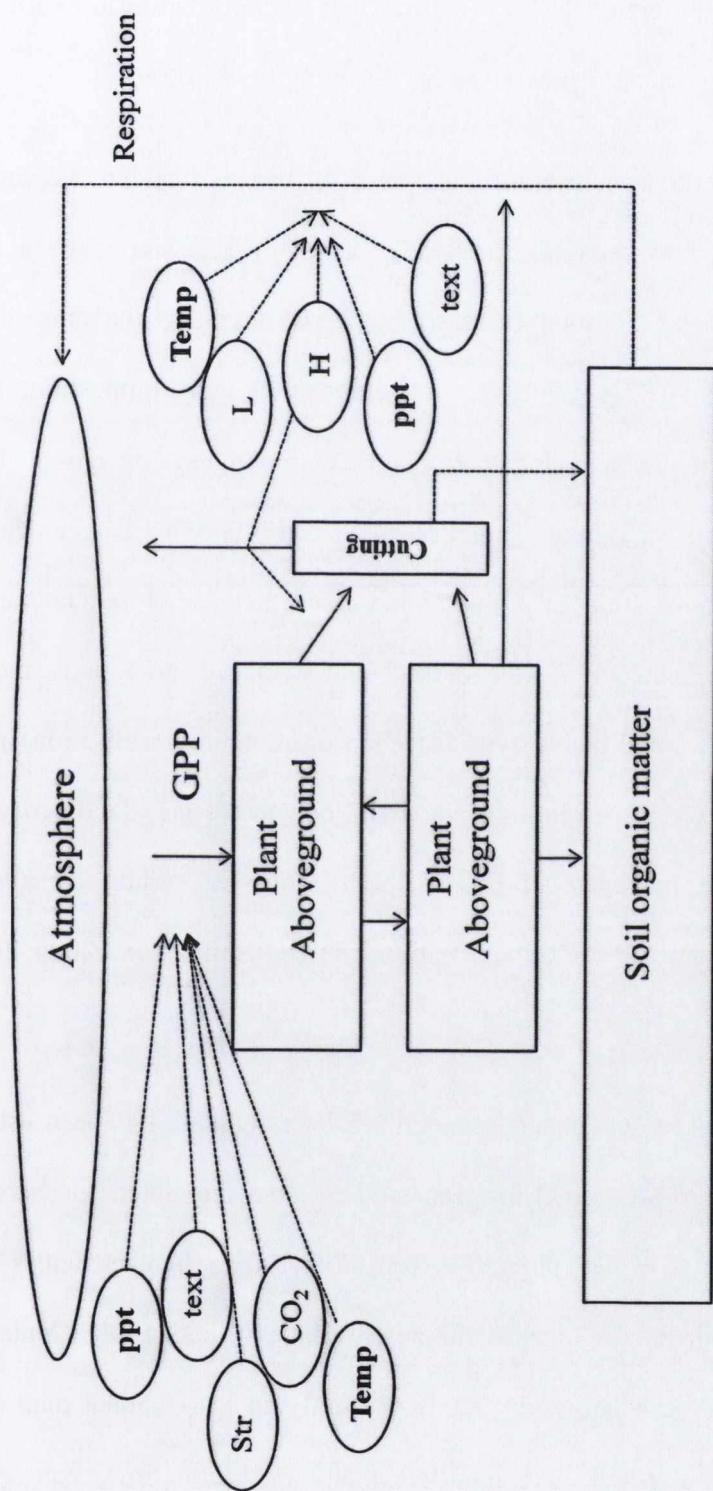


Figure 1.1: Schematic representation of the C budget of temperate grasslands. Stable variables are plant aboveground and belowground biomass, herbivores and soil organic matter. The major C flows are represented in this diagram are net primary production (NPP), and belowground respiration (Resp). Control variables are precipitation (ppt), soil texture (text)m community structure (Str), CO₂ concentration in the atmosphere (CO₂), air temperature (Temp), land use (L) and human intervention (H). Variables studied in this study are highlighted in bold. Adopted from Sala *et al.*, 1996.

relationship between the increase in soil respiration and soil temperature (Q_{10} coefficient). However the extent of the relationship varies among ecosystems and temperature ranges (Peng *et al.*, 2009).

In general, and in an absence of disturbances that remove carbon, the carbon budget of a grassland ecosystem is assumed to a balanced exchange of carbon between the ecosystem and the atmosphere via photosynthesis, respiration, decomposition and combustion. However recent studies have indicated that this is not always the case and in some instances ecosystems do not reach a steady state flux and can continue to act as a net sink of CO_2 (Buchmann and Schulze, 1999; Janssens *et al.*, 2001; Flanagan *et al.*, 2002). For managed grasslands the nature, frequency and intensity of disturbance (including fertilisation) also plays a key role in determining the GHG balance of grassland ecosystems as suitable management options may sequester carbon by a sustained increase in the soil organic carbon content (Smith *et al.*, 2004, Zeeman *et al.*, 2010).

While the relationship between NEE and climate has been established, several short term European studies have attempted to show the net global warming potential from GHG's exchanges with European however it still remains unknown (Batjes *et al.*, 1999; Contant *et al.*, 2001; Soussana *et al.*, 2004). Recently multi – annual data sets have been published and reported that in general European grasslands displayed a net sink for atmospheric CO_2 . In a study based on nine European grasslands Soussana *et al.*, (2007) reported that grasslands

acted as a sink of CO₂ of -240 +/- 70 g C m⁻² yr⁻¹, and Janssen *et al.*, (2003) reported annual NEE may constitute a net sink of -600 +/- 800g C m⁻² year⁻¹, although the uncertainty remains larger than the estimate itself. Using an extended data set Gilmanov *et al.*, 2007 (20 grassland sites), reported that annual NEE varies from significant uptake, -2400g CO₂ m⁻² yr⁻¹, to significant release, 600g CO₂ m⁻² yr⁻¹. More recently Gilmanov *et al* (2010) expanded this analysis to include a global flux tower network of 72 sites and found, on a global level, that grasslands can act as a sink of CO₂ with a mean net uptake of 7900 g CO₂ m⁻² yr⁻¹. However there is significant seasonal and temporal variation in CO₂ uptake and the analysis is required to understand if the existing tower, remote sensing and geographic information systems network are representative of the current distribution of grasslands

More specifically for Ireland, Jaksic *et al.*, (2006) found that NEE in an Irish grassland ranged between -193 +/- 50g C m⁻² to -258g m⁻² in contrasting wet and dry years. Regional variations in NEE are primarily driven by climate gradients (Nemani *et al.*, 2003; Soussana *et al.*, 2007; Yi *et al.*, 2010), as NEE is sensitive to heat and drought and the period of CO₂ uptake which is constrained by temperature dependency on plant growth (Soussana *et al.*, 2007). The climatic effects are complex as they interact differently at various stages in the plant cycle. NEE which is a balance between respiration (R) and GPP is affected by temperature and precipitation differently (Gilmanov *et al.*, 2007b). Where, for GPP temperature outside optimum levels alters CO₂ uptake (through stomatal closure) and the rate of photo-respiration. Furthermore grasslands

comprised primarily of C₃ species, such as *Lolium perenne*, have a lower optimum temperature when compared with C₄ species (Ehleringer *et al.*, 1977; Wedin *et al.*, 1996; White *et al.*, 2000). Water availability also has the potential to alter plant growth inter-annually and from region to region. Plant species are adapted to their ambient climate and have correlated water use efficiencies (water use efficiencies) and rain – use efficiency (RUE). In evaluating the relationship between above ground net primary production (ANPP) and precipitation Belote *et al.*, (2004) showed that vegetation history influences the impact of precipitation on biological activity in a manner that can decrease with increasing precipitation. However, departures from ambient precipitation levels can alter the WUE and RUE of an ecosystem.

Total ecosystem respiration (R_h and R_a) is more sensitive to changes in temperature levels due in part to the influence temperature has on enzyme activity. In a normal temperature range a Q₁₀ co-efficient can be used to define the relationship between soil temperature increase and soil respiration (Kirschbaum, 2006), which varies between ecosystems and temperature ranges, and suggests that soil respiration increases with increasing temperature. Precipitation also affects the rate of soil respiration. Wang and Fang (2009) analysis on global respiration rates found that increased precipitation resulted in increased soil respiration, however for rainy regions this decreased as precipitation levels increased, due in part, to limits on aerobic respiration.

In addition to this many types of grassland are currently under some form of management, such as fertiliser inputs and frequent cutting/ grazing management. Currently this can lead to higher SOC stocks than in natural systems (Contant *et al.*, 2001). However on farm scale grasslands can be a source of CO₂ emissions (Byrne *et al.*, 2006) and as a climate change progresses grasslands themselves may become a source of CO₂.

In the absence of longer term experimental data empirical models do not confirm that grasslands will act as a carbon sink as they rely on the concept that an equilibrium will be reached for all soil organic C, additionally these results also indicate that due to their climatic sensitivity grasslands CO₂ uptake will be affected by future climate change. Global climate models currently predict altered precipitation patterns and temperature levels (see next section for description) therefore studies need to investigate the impact of climate change grasslands under current management practices.

1.4 Global climate change

As stated in section 1.1 rising concentrations of GHG's have lead to a change in the composition of the earth's climate. This had lead to a need by national governments to quantify the extent the climate will change into the future, the effects of such change will have on both natural and managed ecosystems and also a need to formulate mitigation strategies which will limit GHG concentration increases. As a consequence Global

Climate Models (GCM's) have been developed to enhance the understanding of global climatic processes (Sweeney *et al.*, 2002). On a global level, GHG emission scenarios, which are used to drive climate change scenarios, are based on a number of key assumptions such as population and economic growth and energy consumption which all are subject to large uncertainties. Therefore over time the IPCC (1996, 2000 and 2007) have developed and evolved a number of emission scenarios based on updated trends in the inputs and also governmental policy and cover a wider range of emissions (Sweeney and Fealy, 2002). These scenarios are termed SRES scenarios, and each can have a different effect on future climate change. However overall estimations from GCM's using all these scenarios predict that the average surface temperature is likely to increase by 1.8 to 4.0°C over the period 1990 to 2100 coupled with an increasing occurrence of extreme drought and precipitation events as precipitation patterns change depending on an area's location. In addition sea levels are projected to rise by 0.18 to 0.59 meters over the same period (IPCC, 2001, 2007).

1.5 Climate change in Ireland

For Ireland, the EPA (2003) produced a climate change scenario based on the SRES B2 scenario these predictions formed the basis of the experimental change in temperature and precipitation changes we will apply to monocultures of *Lolium perenne* (Chapter 2).

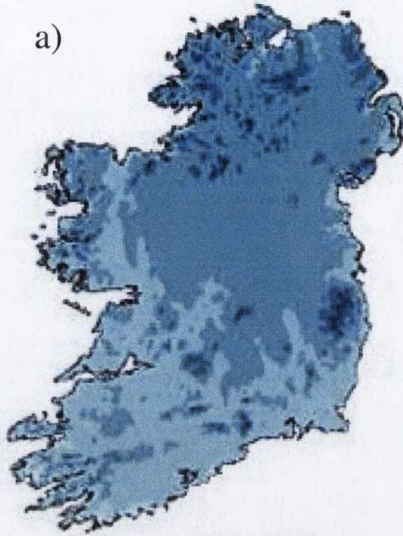
Figure 1.2 (a and b) shows the modelled temperature in January for two, 30 year intervals, i.e. the 2050's and 2080's. Average January temperatures are expected to range from 6 to 7.5°C over much of Ireland and between 7.5 – 9°C along the southern coasts. This in turn reflects an increase of 1.5°C for 2055 and 2.5°C for 2075 in mean temperatures is expected with respect to the 1961 – 1990 average. Figure 1.2 (b) shows the mean July temperatures for the same periods. Increases of approximately 2°C are expected with the highest values to be found inland (EPA, 2003).

Patterns in precipitation changes are less reliable to predict as there are quite large fluctuations in multi-year precipitation levels affect background (1961 -1990) averages. However GCM's have allowed for predictions to be made with some certainty. Figure 1.3 (a) represents modelled precipitation levels in January for two thirty year periods, 2050's and 2080's. On average across the winter months there is an increase of approximately 11% in precipitation levels compared with the 1961 – 1990 baseline. Figure 1.3 (b) represents modelled precipitation levels for July for the same time periods. Nationally there is a reduction in the levels of precipitation of approximately 15% with decreases of over 40% in some parts (EPA, 2003). In general for Ireland by the year 2055 it is expected that there will be a 15% increase in winter precipitation, 15% decrease in precipitation during the summer months coupled with an overall increase of 2°C in temperature across all seasons. More specifically for use in this project, the downscaled data from the GCM model provided us with 852 10 x 10km grid cells for

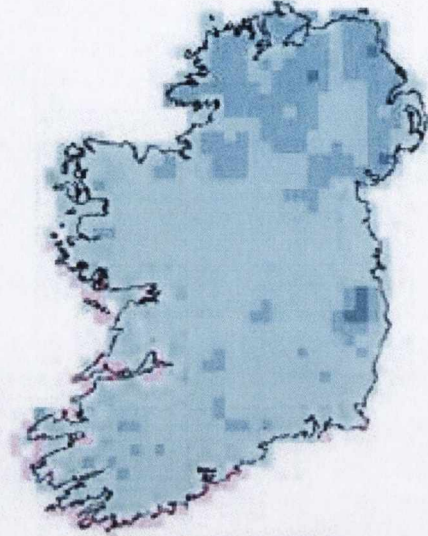
Ireland, where in each cell the monthly change in climate from 2001 to 2055 is clearly defines. Therefore by selecting the grid cell for the Carlow region, where the experimental site is located, we used this specific climatic data to create a stepwise series of changes in temperature and precipitation to create a control (ambient) and treatment (near 2055 climatic conditions), details of the control systems are provided for in chapter 2.

Mean Temperature

a)



January 1961-1990

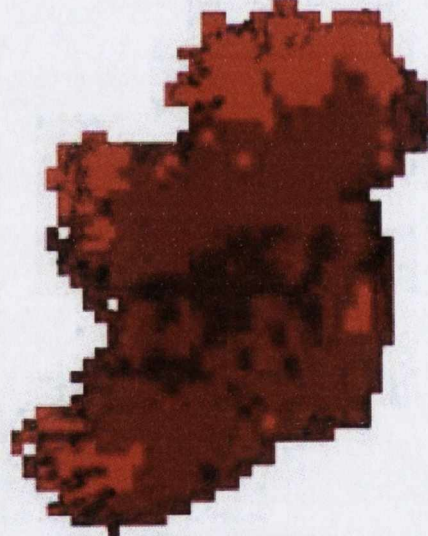


January 2041-2070

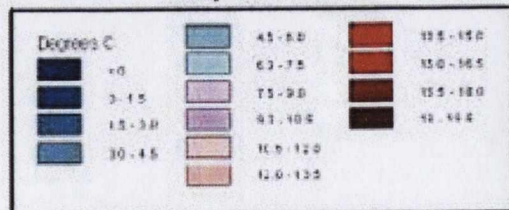
b)



July 1961-1990



July 2041-2070



Maps produced by Rowan Fealy
and John Sweeney, NUI Maynooth

Figure 1.2: Mean annual temperature for (a) January for the time periods 1961 to 1990 and 2041 – 2070 and (b) July over the two same time periods *Source EPA, 2003.*

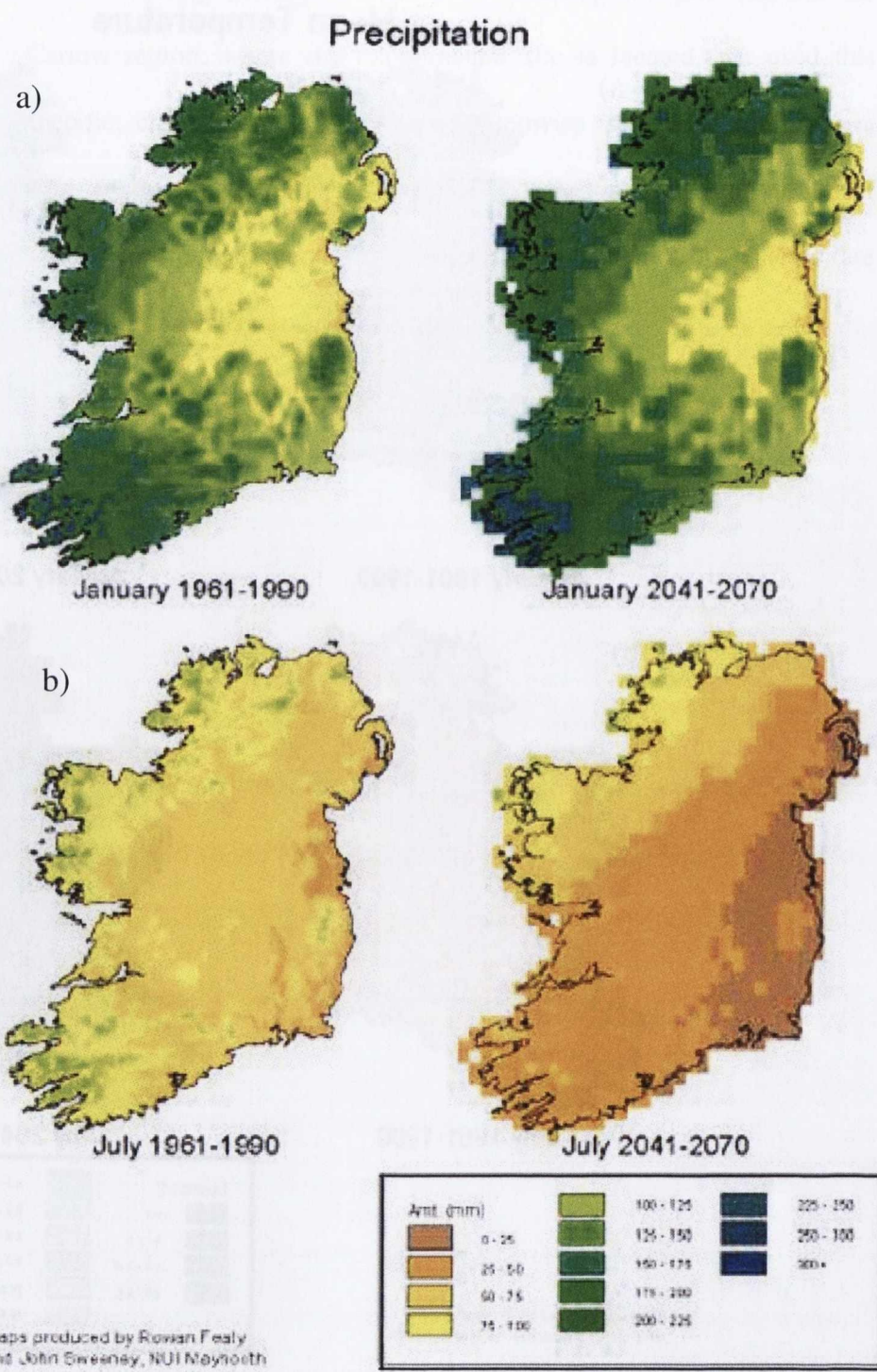


Figure 1.3: Mean annual precipitation for (a) January for the time periods 1961 to 1990 and 2041 – 2070 and (b) July over the two same time periods *Source EPA, 2003.*

1.6 Motivations and objectives of the thesis

While GHG's emissions from pasture are intimately linked to current management practices and the ambient climate (Hopkins *et al.*, 2007; Gilmanov *et al.*, 2007), uncertainty remains how the future climate will affect the productivity of European grasslands and if under their current management regime will they become a source of CO₂ as climate change takes effect.

In an Irish context grasslands are the dominant ecosystem type, accounting for 90% of agricultural land which translates to 56% of total land area and is the primary resource for almost all of our agricultural output (Cruickshank *et al.*, 2000) and as a consequence a changing climate will impact on the GHG budget and the ability of grasslands to remain productive. Furthermore, as signatories to the Kyoto Protocol, Ireland has committed emission targets into the future. As agriculture accounts for 27% of Ireland's total GHG emissions (McGettigan *et al.*, 2006) consideration must be given to the impact of future climate change on Irish grasslands. Consequently the main research objectives of this dissertation are:

- To propose the use of the microcosm system (described in the section 2.2) to replicate both the ambient climate and future climate (2050) and expose swards of *Lolium perenne* to the two climate treatments

- To calculate and examine differences in NEE and productivity for both the *Lolium perenne* sward treatments across all seasons
- Assess the impact – either positive or negative – that a changing climate will have on the productivity of Irish grasslands.
- Define future research needs and questions that will need to be addressed by policy makers in Ireland.

1.7 Outline of thesis

Chapter 1: Provides a background of the study, including motivations and objectives of the thesis. A description of the key components of carbon in both terrestrial and grassland ecosystems, the potential impact of climate change in Ireland is provided.

Chapter 2: Outlines the theory behind the development/working of measurement chambers. Includes detailed technical descriptions on how the CO₂ flux, temperature and precipitation control systems work. Outline of supplementary measurements carried out. Outline of the determination and subsequent application of the future climate.

Chapter 3: Presents the results of the temperature and precipitation recorded within the microcosms. Also compares the performance of the microcosms in terms of simulating a percentage difference between them.

Chapter 4: Calculations of NEE and its primary components, GPP and R, within the monolith system. Here we present the daily, monthly and

yearly values and also the soil respiration, biomass and gap filling results.

Chapter 5: The impact of climate change on grassland NEE

Chapter 6: Discussion, conclusions and perspectives arising from this thesis

Chapter 2:

Chapter 2: Outlines the theory behind the development/working of microclimate chambers. Includes detailed technical descriptions on how the CO₂ flux, temperature and precipitation control systems work. Outline of supplementary measurements carried out. Outline of the determination and subsequent application of the term climate.

Chapter 3: Presents the results of the temperature and precipitation recorded within the microclimate. Also compares the performance of the microclimate in terms of fluctuation & percentage difference between them.

Chapter 4: Calculations of GPP and its primary components, GPP and R, within the glasshouse system. Here we present the daily, monthly and

2: The use of the multiple microcosm enclosure facility to assess the impact of climate on NEE

2.1 Site description

The study was conducted at Teagasc, Oak Park, Research Centre Co. Carlow, Ireland ($52^{\circ} 51' \text{ N}$, $6^{\circ} 54' \text{ W}$, 50 m above sea level) (Figure 2.1). The climate is oceanic with no extremes of temperature. The mean annual temperature is approximately 9.7°C with a summer mean daily maximum of approximately 19°C and winter mean daily minimum of about 2.5°C . The average rainfall is 99.8 mm (averaged over a thirty year period, Met Eireann, 2007).



Figure 2.1: Oak Park research centre, Carlow, Ireland: location of experimental research site

2.2 Microcosm enclosures

Microcosm enclosures permit realistic comparisons of an ecosystems response to different climatic factors, as they have an automated environmental control system which is coupled with a gas exchange monitoring facility. The microcosms used in this study consisted of a below ground soil compartment termed monolith of 0.2 m^3 (L1.2 x W 0.5 x H 0.3) and an enclosed aboveground compartment of 0.5 m^3 (L1.2 x W 0.5 X H 0.5) (Figure 2.2). The canopy enclosure consists of a metal frame covered with a transparent polyethylene film (60 μm gauge), that was attached to ridged polycarbonate end units using Velcro. This allowed for an airtight seal to be created when the monolith was closed but also allowed for each enclosure to be easily opened on a weekly basis for access to the vegetation for measurements. One of the polycarbonate end units in each chamber was fitted with two plastic tubes, both 8 cm in diameter and 5 cm in length, which were used as air inlets and outlets (Figure 2.2 (a and b)). The soil is contained in single steel containers with a small hole at the bottom to allow for drainage. Additionally each microcosm is fitted with soil and air temperature probes, soil moisture probes and PAR / Tube solarimeters which records these environmental variables on a continual basis.

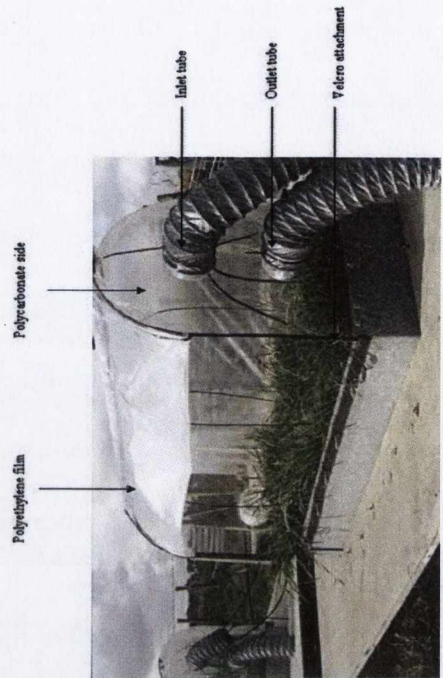
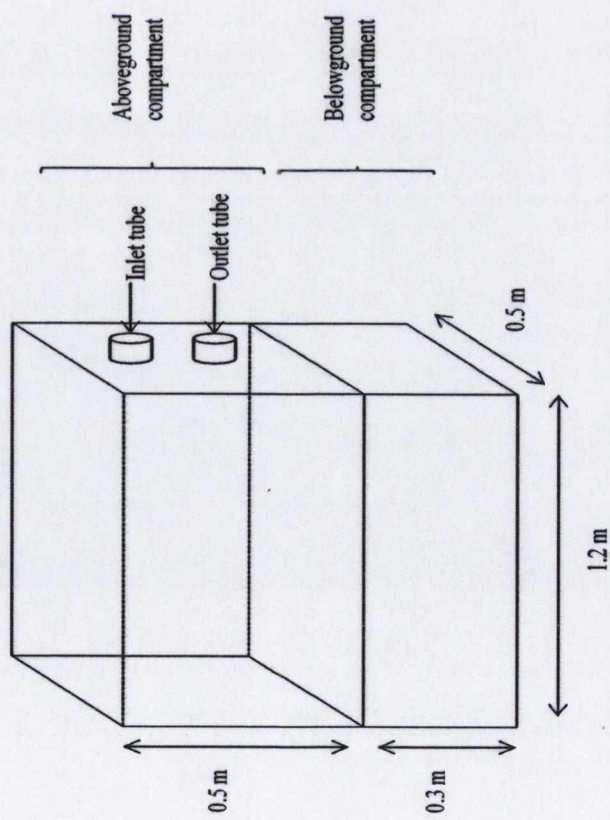


Figure 2.2: A schematic representation of a microcosm (a) and a microcosm *in situ* (b) at the Oak Park research centre, Co. Carlow.

The research facility, based at Teagasc Research Centre, Oak Park, Co. Carlow contained eight microcosms (Figure 2.3). For this study, 4 microcosms were assigned to track the ambient temperature and precipitation and the remaining 4 microcosms were assigned to a changed climate scenario which applied a monthly percentage increase in temperature and a either a monthly decrease or increase in precipitation based on modelled climate change estimates.

The following sections give a description of the different sensors used for data collection and the management strategies and protocols followed in order to establish the partially controlled climatic conditions in the monolith chambers.



Figure 2.3: The microcosm chambers *in situ* in the Oak Park research centre, Co. Carlow.

2.3 Description of instruments

2.3.1 Tube Solarimeters

Incident solar radiation was measured using tube solarimeters (Delta T Devices) which are designed to average the irradiance on the horizontal plane (in kW m^{-2}) where the distribution of radiant energy is not uniform (i.e. within foliage). Their tubular construction also minimises disturbance when inserted into the foliage. The incident energy flux results in a temperature difference between the black and white alternating areas on the light detecting surface, which generates a voltage output from the copper constantan thermophile (Figure 2.4). The element is protected by Pyrex glass which limits its response to visible and infra-red radiation. The solarimeter measures the total solar irradiance (0.35 – 2.5 μm) incident on its upper surface and the output voltage is given with a conversion factor of 15 mV/ kW m^{-2} (Delta – T Devices, 1993) i.e.

$$\text{Irradiance} = \text{measured voltage (mVolts)} / 15$$

Tube solarimeters were placed at a height of 1.5m outside, to provide a direct reading of site radiance and within the chambers and were cross calibrated with a net radiometer in an adjacent site.

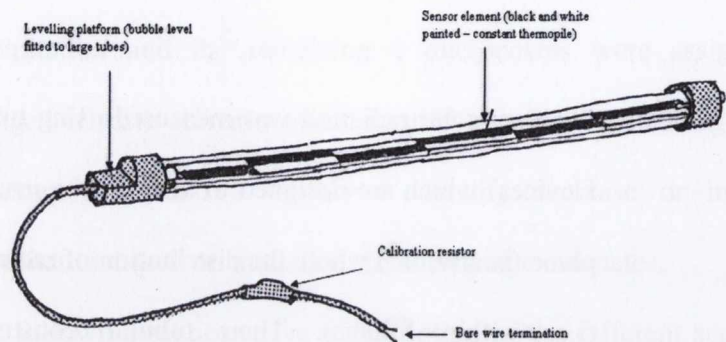


Figure 2.4: A schematic representation of a tube solarimeter. *Source* Delta – T, tube solarimeter user manual, 1993

2.3.2 Soil moisture probes

The volumetric water content of the soil monolith was measured to a depth of 30 cm using CS615 time domain reflectometers (TDR, Campbell Scientific). Each TDR consists of two 30 cm steel rods configured to a bistable multi-vibrator. These oscillate depending on the permittivity of the material surrounding the steel rods. When inserted into the soil the level of oscillation, when converted using a calibration equation (Campbell, 2002), gives the water content of the soil (Figure 2.5). Prior to use in this experiment each reflectometer, both in the microcosms and the external probes, were calibrated. Sixteen soil samples were collected from the original grassland site from which the soil monoliths were extracted and packed into industrial buckets (height

= 42cm and width 60cm), then weighed and oven dried until a stable weight was reached. Each TDR probe, connected to a Cr10x data logger, was inserted horizontally to an oven dried sample and the value recorded by the Cr10x logger was set to zero. The soil was then gradually rewetted by adding 10mm of water at a time and each probe reading was checked to ensure that the values read by each TDR was the same. This calibration was repeated to ensure the accuracy of the readings.

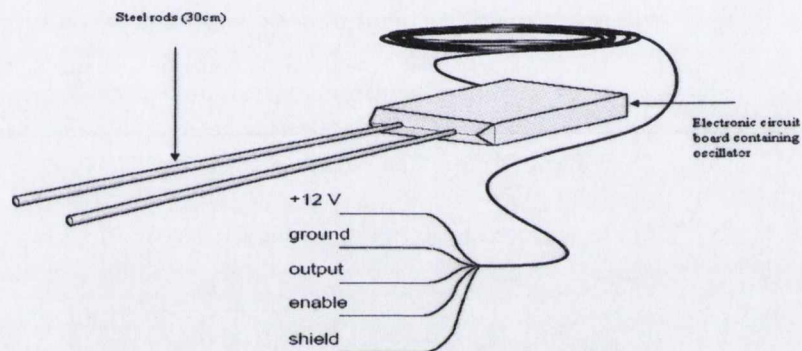


Figure 2.5: A schematic representation of water content reflectometer.
Source: CS615 water reflectometer user manual, 1996

2.3.3 Air and soil temperature

Both soil and air temperatures in the monoliths were measured using thermocouples. Each thermocouple consists of wires made of two different metals that produce a voltage proportional to a temperature difference. Each thermocouple was calibrated before instillation in the

monoliths. Air temperature thermocouples were shaded from direct solar radiation.

2.3.4 Soil respiration

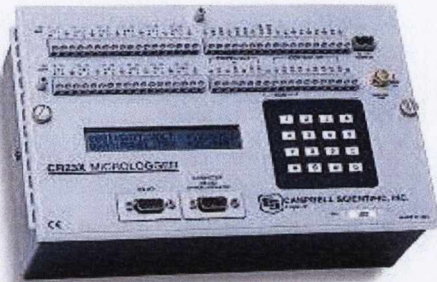
Soil respiration measurements were made using an EGM-4 CO₂ Gas Analyzer and SRC-1 Soil respiration chamber (PP Systems International, USA, Figure 2.6). When the chamber is placed on the soil, gas emitted from the soil accumulates within the respiration chamber, and the CO₂ concentration of the air is sampled for 120 seconds or until the rate of CO₂ increase has reached a steady state, and the rate of CO₂ flux is calculated based on the linear increase of CO₂.



Figure 2.6: EGM – 4 CO₂ gas analyzer and SRC – 1 soil respiration chamber. *Source: PP Systems.*

2.3.5 Data loggers

(a)



(b)

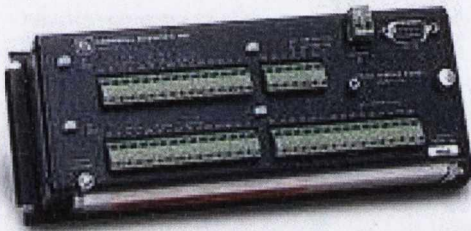


Figure 2.7: (a) Cr 32x datalogger
(b) Cr 10x datalogger *Source:*
Campbell Scientific
User Manual.

The Cr32x (figure 2.7a) was used to record and store measurements of temperature (soil and air), radiation and also open/close the valve system for sampling air in each of the canopy enclosures (see later for more detail). Figure 3,7 b illustrates the Cr10x which was used to control the irrigation system in each microcosm and record the soil moisture content on an hourly basis.

2.4 Experimental design, measurements of NEE and climate manipulation

To assess the effect of a changed climate on the carbon balance of a grassland dominated by *Lolium perenne*, eight soil monoliths were extracted from a long term pasture which had not been re-seeded for approximately 30 years using a U-shaped blade pulled behind a tractor which extracted an intact monolith. Each monolith was then re-sown with monocultures of *Lolium perenne* var. *Cashel*. To simulate current management practices the grass sward was harvested in all monoliths, five times during each growing season. Fertiliser applications were made in line with the Nitrates Directive which came into force in 2005 where for example the application of nitrogen and chemical fertilisers is prohibited between the 15th September and 12th January. Therefore for each microcosm 6.25g of fertiliser applied after the first cut and 5g after subsequent cuts. The management practices and timing of cutting/fertiliser application were the same for both the treatment (future climate) and control (current ambient) monoliths.

As outlined in section 2.1 microcosm enclosure facilities have an automated environmental control system which can either track the ambient climate or, as this experiment requires, allows us to manipulate the climatic parameters: temperature and precipitation.

Sections 2.4.2 and 2.4.3 outline in detail how changes in temperature and precipitation are replicated within each of the microcosms, however in general, the projected change to the climate parameters are based on the

outputs from Sweeney *et al* (2002). These outputs consisted of modelled monthly changes in temperature and precipitation from the ambient climate and are outlined in table 2.1. To incorporate a realistic seasonal and inter-annual variability we then applied the percentage change in both temperature and precipitation (table 2.1), where the difference is based on the time of the year, to the measured ambient climate recorded at the experimental site. The ambient climate was in turn, replicated within the four control microcosms.

	Precipitation	Temperature
	% difference	% difference
January	3	24
February	16	23
March	3.5	16
April	12	24
May	-10	17
June	13	17
July	-55	16
August	-39	16
September	-18	12
October	8.5	19
November	2.8	17
December	5.2	19

Table 2.1: The modelled percentage difference in temperature and precipitation values for each month as outlined by Sweeney *et al* (2002). Positive values denote an increase in temperature and precipitation must be applied to the treatment microcosms, negative values denote that a decrease in temperature or precipitation to be

2.4.1 *The gas exchange facility*

Unlike open systems, such as open top chambers and free air CO₂ exposure systems (FACE), a canopy enclosure is essentially a closed transparent flow through cuvette where we can manipulate the internal climate to either track ambient conditions or to impose defined changes in the environment. Air entered each canopy enclosure at an average flow rate of 500 Lmin⁻¹. With the internal volume of 500 L per enclosure the air exchange rate was approximately 60 times per hour. To prevent interference from atmospheric CO₂ the outflow was restricted sufficiently to ensure the maintenance of a small positive pressure within each monolith. The airflow into each chamber was measured weekly using an anemometer, and these values were used in the calculation of CO₂ fluxes.

As discussed in chapter 1, NEE, is the amount of carbon dioxide assimilated by a plant minus any losses via autotrophic and heterotrophic respiration. It is directly measurable through the quantity of CO₂ taken up or lost by the plant coupled with estimates of soil respiration. Consequently during the daytime, the atmospheric [CO₂] is depleted relative to the incoming gas concentration due to carbon uptake by the plants. At night-time the air flow is enriched in CO₂ relative to the incoming concentration due to respiration. Therefore by knowing the initial and final [CO₂] of air passing over an enclosed canopy we can determine NEE of an ecosystem in a non destructive manner (Figure 2.8).

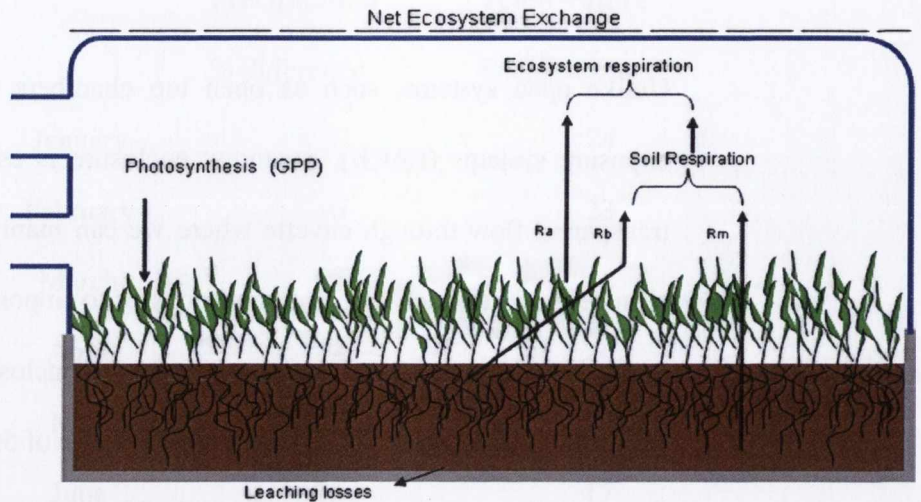


Figure 2.8: Components of NEE measured within each individual monolith

A computer controlled multi valve system sequentially sampled both reference and analyses air samples from each canopy enclosure for 7 minutes every hour, with the first two minutes of each sample period being discarded from flux calculations to eliminate interference from other chambers. Air from each chamber was passed through the reference and analysis line of an infra-red gas analyser (LCA-4, ADC UK) and the $[CO_2]$ for each sample along with the differential was stored. The zero of the IRGA was checked automatically every hour by passing reference air through both the analysis and reference line. Aboveground CO_2 fluxes were calculated from changes in CO_2 concentrations and measured air flows according to:

$$F_c = (f/A) (C_o - C_i) / M_v$$

Where A is the area (m^2) of the monolith, M_v is the density of air (kg/m^3), $C_i - C_o$ is the change in CO_2 concentration measured in $\mu\text{mol m}^{-2} \text{s}^{-1}$ and f is the rate at which air is passed through the canopy enclosures ($\text{m}^2 \text{s}^{-1}$). All fluxes were expressed as $\mu\text{mol CO}_2$ per m^2 per second. Fluxes were calculated for every five minute sampling period and these were summed to give the daily, weekly and monthly values. For this experiment, the net uptake of CO_2 by the grass sward is denoted by positive values, and negative NEE values represent the net release of CO_2 to the atmosphere through respiration.

In the daytime, NEE is given by above ground canopy assimilation (GPP) of CO_2 and additional soil respiration (R_s) measurements (as described above) fitted to soil temperature using a Q_{10} model (Amothor, 1989) to calculate the total NEE. At night, NEE is comprised of both plant and soil respiration (R_p).

To ensure the accuracy of the gas exchange facility the IRGA was calibrated on a monthly basis. To do this the reference cell was flushed through by using a calibration gas of 630 ppm (BOC gases) whose flow rate through the gas analyzer by a regulator and flow meter, this was primarily to prevent damage by over pressure. In addition the soda lime and silica gel was frequently replaced.

2.4.2 Soil moisture control system

The soil watering control system consisted of nine calibrated automated time domain reflectometry systems (TDR 100, Campbell Scientific, Logan, UT, USA) to record the soil water content (SWC) (see above), a Cr 10x data logger (Campbell Scientific, USA) to measure and control watering levels within each microcosm and irrigation piping that delivered water directly to the soil surface. One of the nine TDR's was located in an adjacent grassland, tracked and recorded changes in soil moisture content on an hourly basis, this was used to determine the ambient soil moisture content and hence the soil moisture content of the control microcosm. The irrigation system within each microcosm operated independently so that if the moisture level within a single microcosm fell below the external reference level, the irrigation system was instructed to apply water to the microcosm until the correct soil moisture content was reached.

For the changed climate treatment the downscaled data from Sweeney *et al.*, (2002), to determine if there was either an increase in the level of precipitation or decrease (Table 2.1). At the start of each month the predicted percentage change in precipitation level was written into the datalogger control system, so that the soil moisture content was held at the recorded value given by the external TDR plus or minus the calculated difference.

2.4.3 Temperature control system

As with the irrigation and the gas exchange facility, the temperature control system was also automated. For the control treatment (ambient climate) external air was pumped initially into an external mixing chamber and then fed directly into each chamber where the internal temperature was monitored and recorded using thermocouples. The flow rate into each monolith could be controlled by the individual pumps if required and any changes to the flow rate was recorded and used in any subsequent calculations of the CO₂ fluxes.

As with the control, the four treatment microcosms had individual pumps that regulated the rate at which air flowed into each chamber. However, the air in these enclosures was pre-heated in an external reservoir, which was equidistant from each treatment microcosm (Figure 2.9) and then fed into the treatment monoliths. Upon entering the treatment microcosms the temperature was recorded and the level of increase was adjusted using an internal thermostat inside the external chamber. The temperature difference between the ambient and treatment monoliths was also adjusted on a monthly basis as given in Table 2.1.

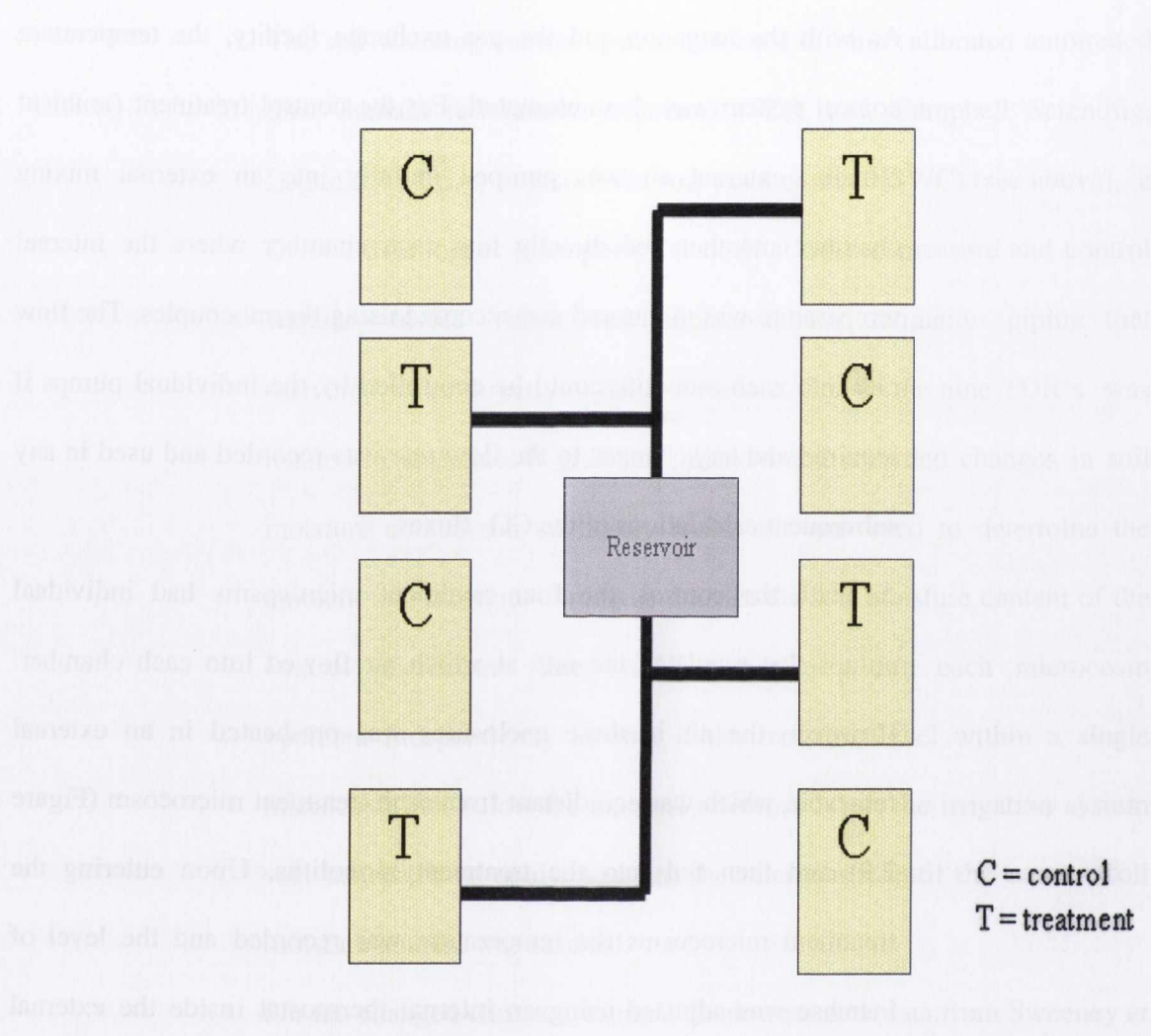


Figure 2.9: Schematic representation of the position of the treatment monoliths (T) with regards to the central reservoir. Each of the four treatment monoliths has an individual pipe leading from the central reservoir and air temperature is recorded upon entering each chamber

2.4.4 Supplemental measurements

As has already been explained, while the gas exchange facility allowed me to calculate ecosystem CO₂ exchange, measurements of soil respiration and biomass production were necessary for a more detailed assessment of ecosystem carbon budget. Consequently on a weekly basis, three replicates of daytime soil respiration were made for each chamber using an EGM-4 CO₂ Gas analyzer and SRC-1 soil respiration chamber (PP systems, Amesbury, MA, USA). Additionally three measurements of sward height within each monolith were made. In addition, repeat cuts of the sward were made during the growing season in order to simulate management of the grass. The *Lolium perenne* was cut to leave a 5mm stubble height and the biomass that was removed was dried and weighed to determine harvestable yield.

2.5 Data processing and subsequent statistical analysis

Figure 2.10 outlines the data processing protocol that was followed after both the climate and CO₂ flux data was downloaded from the site data loggers and IRGA gas analyser. As stated previously climatic data in all microcosms was recorded hourly therefore, once downloaded, recorded values were separated into the four replicates (n=4) (Figure 2.10, a). Following this we then performed an analysis of variance (ANOVA) between the four replicates to test that each microcosm is performing correctly and then using the average values we checked that the expected

difference between the treatment and control was being replicated. Once all the annual data was compiled we then performed another ANAOVA to test for differences between the average temperature and soil moisture content recorded in the treatment microcosms in 2008 with recorded values over the same months in 2009. This was repeated for the control climatic variables and was to test if there was in interannual variation in the climatic variables. In addition to directly test if there was a statistically significant difference between the treatment and control recorded in 2008 we performed an additional ANOVA, this was repeated for 2009

Unlike the climatic variables, the IRGA recorded the differences in carbon dioxide concentrations in a sequential cycle for seven minutes every hour in each of the microcosms. Therefore to calculate the hourly CO₂ flux for each microcosm we initially assigned the recorded values to a microcosm based on the time it was recorded, and once the initial two minutes were discarded we then took the average from the remaining values (Figure 2.10 b). Once data was discarded due to for example interference by the microcosms being opened the CO₂ flux value for each hour was then calculated based and missing data was gap filled based on the protocol outlined in section 2.4.5. Following this we then performed an ANOVA analysis to test that the monocultures of *Lolium perenne* were performing in a similar manner and then NEE was separated into GPP and R as outlined in Section 5.2.3. Finally as with the climatic datasets, we performed a number of statistical tests to demonstrate that there was an interannual variation in CO₂ fluxes

between the treatment and control CO₂ fluxes and also if there was a statistically significant difference between the treatment and control fluxes within each year. All statistics were performed using Mini - Tab.

2.6 Gap filling exercise

Due to instrument and equipment failures, there were inevitably periods of time when it was not possible to make continuous flux and climate measurements. In order to ensure that continuous data was available for constructing whole season carbon budgets it was necessary to fill gaps in the missing data. However the relationship between temperature, precipitation and light levels with NEE and its components: GPP and R, varies depending on the time of year and also for example if harvesting has taken place (see Section 4.1 for results). Therefore, for daytime gaps where they existed a light response curve was fitted to the hours/days immediately preceding the gap which plotted net photosynthesis against light intensity. More specifically, in an excel macro, with help of the solver function, a irradiance versus photosynthesis was plotted and then, the "solver" looked for the best fit (minimal root mean square error between predicted and observed values). Night time gaps were filled in the same manner, however as respiration correlated well with soil temperature this dependent variable, therefore for the relationship between soil and CO₂ fluxes in the period immediately preceding the gap was used to fill data gaps.

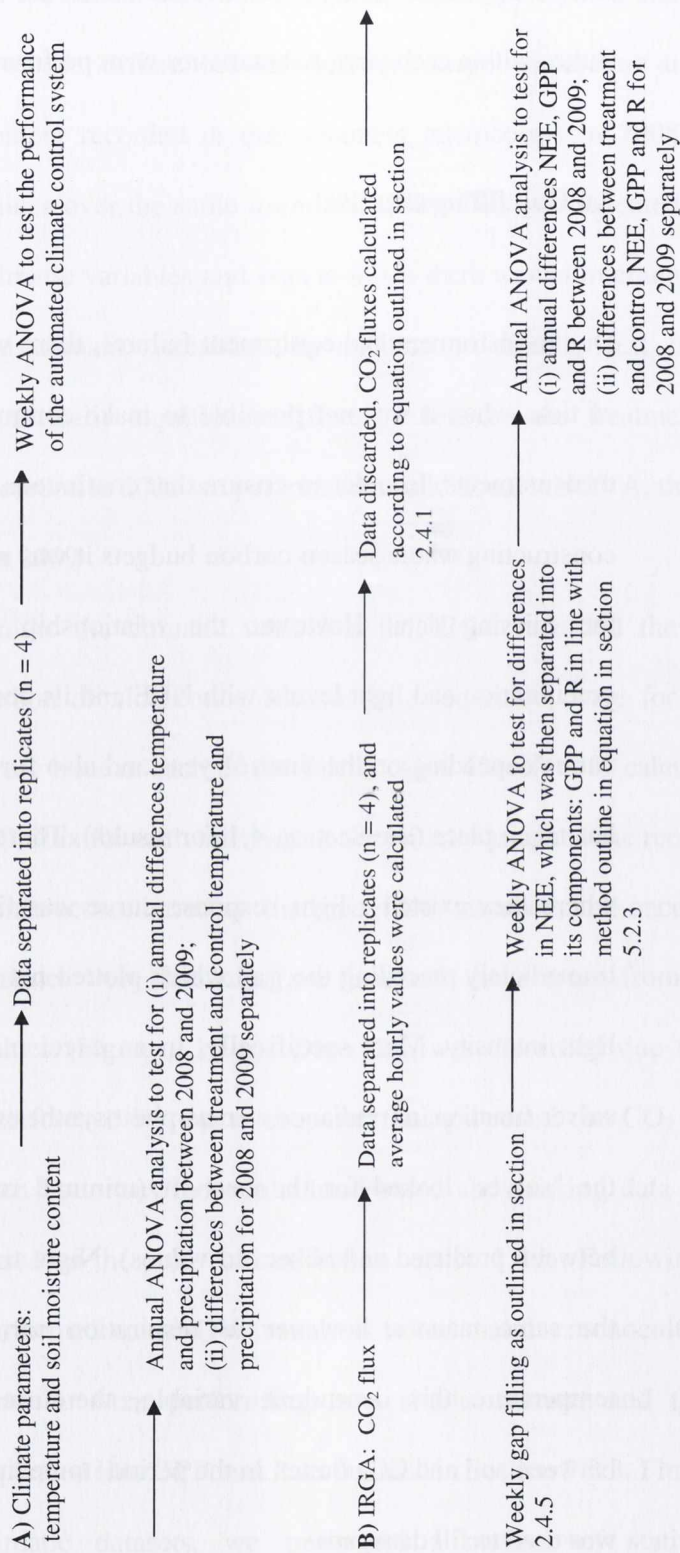


Figure 2.10: Schematic representation of the data processing and subsequent statistical analysis that was carried out for the a) climatic variables and b) carbon dioxide downloaded from the Oak Park Research Centre, Carlow

Chapter 3

3: Climate results: replication of the ambient and changing climate within the microcosm enclosure

3.1 Data collection

Ambient (control) and treatment (climate change scenario) climatic data such as soil and air temperature, solar radiation and soil moisture were monitored for the duration of the experimental period. Each parameter was read at one minute intervals and recorded at 1 hour intervals for each microcosm. The values presented as the treatment and control are calculated as an average across the 4 replicates of each. Due to electrical failures during the experiment gaps have appeared in the experimental data on June 7th to June 9th, September 1st to the 5th and November 18th in 2008, March 19th to 20th, April 1st to April 4th and June 3rd to June 7th in 2009. In cases where the missing data was only for a 24 hour period, missing data was filled with data from the same time period in the preceding day. However for longer periods this is not an appropriate approach to make for longer periods in time, therefore data was filled by using climatic data obtained from an adjacent experimental site. The following sections outline the temperature and precipitation values recorded in the microcosms in 2008 and 2009, the results of the statistical ANOVA we performed as outlined in Figure 2.10. And finally the difference between and how they compare with modelled estimates presented by Sweeney *et al* (2002).

3.2 Air and soil temperature: Inter-annual values recorded in the control and treatment microcosms

3.2.1 *Control microcosms*

As outlined in Sections 2.5, the hourly temperature values recorded in each of the control microcosms were tested to check that the each of them were performing in a similar manner, and across both years we found that there was no statistically significant difference between the replicates ($n=4$, $P<0.05$). Figure 3.1 and 3.2 therefore represents the average hourly temperature ($^{\circ}\text{C}$) recorded in 2008 and 2009 and the standard error between the replicates. However due to the size of the data set the standard error is only shown in two week intervals.

Over the months where the experimental measurements overlapped there was a difference in the mean temperatures of the control microcosms at the experimental site (14.1°C) in 2008 and (12.7°C) in 2009. Average monthly temperature ranged from 7.2°C in March 2008 to a peak of 19.92°C in August 2008 and 7.05°C in February 2009 to 18.56°C in 2009. Figures 3.3 and 3.4 represent the average hourly soil temperature over the same periods in 2008 and 2009 recorded in the control microcosms. On a daily basis soil temperature follows the same pattern as daytime temperature changes however the difference between night and daytime values were less variable when compared to changes fluctuations in air temperature. The mean annual soil temperature at 5cm for the duration of the experiment in the control microcosms was 11.22

°C in 2008 and 12.22°C. The monthly mean air and soil temperature for the control microcosms, with the standard deviation in the range of values recorded over the month is given in Figure 3.5 (a) and (b). As expected for both years the air temperature increases from April to reach a peak in August and temperatures were rarely below zero degrees and as a consequence little frost or snow was noticed during the study period. The peak growing period for *Lolium perenne* typically occurs between March and September in line with the observed increasing temperatures observed over both years of the experimental period. The average monthly air and soil temperature was higher in March, April and May 2009 at 8, 13.5 and 15°C respectively compared with 7.2, 7.7 and 10.79°C for the same period in 2008. However, towards the end of the peak growing season, for example September, average monthly soils and air temperatures were higher. While there are small differences in the average temperatures recorded over both years, the ANOVA (table 4.4) show that there was no statistically significant difference in the interannual temperatures in the period where the experimental measurements overlap.

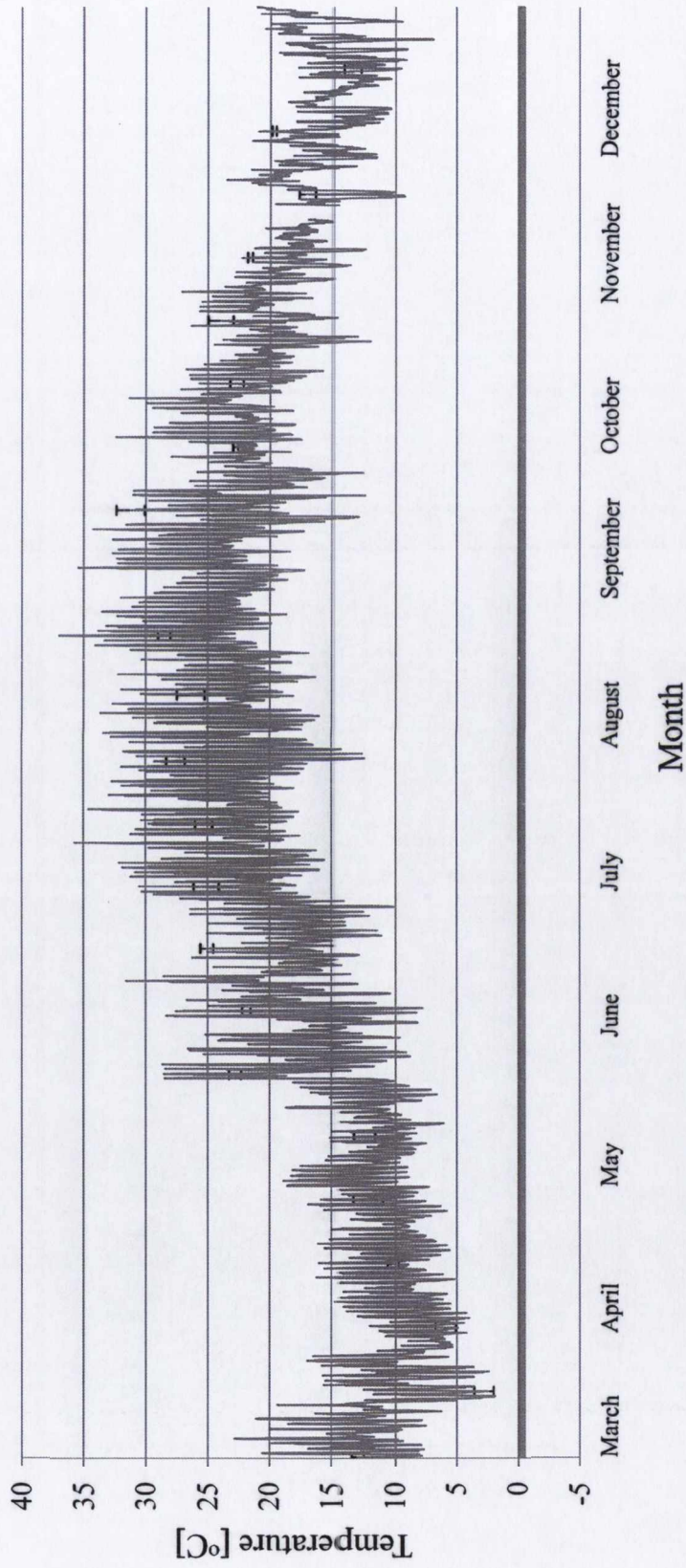


Figure 3.1: Average hourly air temperature (°C) recorded in 2008 for the control microcosms, data is averaged across four replicates (n=4) and there was no statistically significant difference between the replicates ($P < 0.05$), Bars represent the standard error in recorded temperature at two week intervals

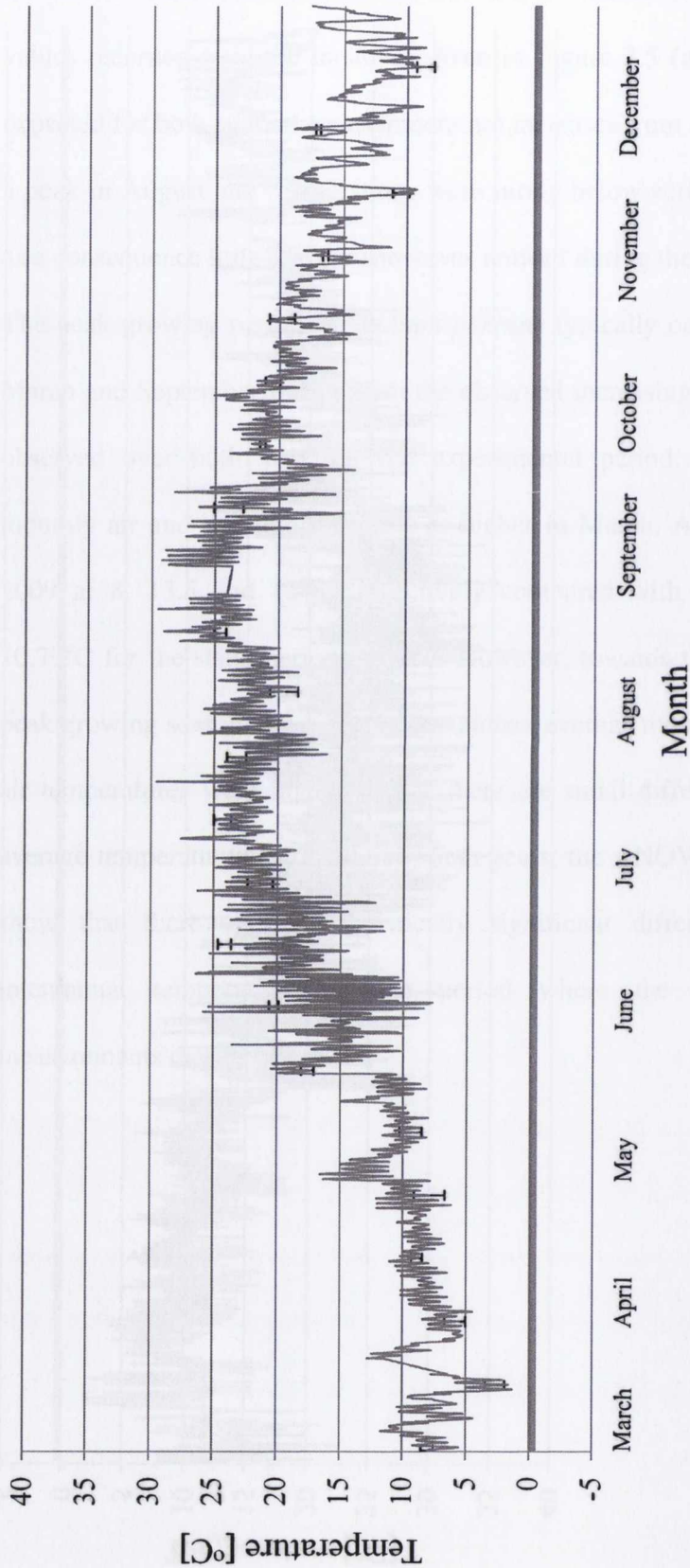


Figure 3.2: Average hourly soil temperature (°C) recorded in 2008 for the control microcosms, data is averaged across four replicates (n=4) and there was no statistically significant difference between the replicates ($P<0.05$). Bars represent the standard error in recorded temperature at two week intervals

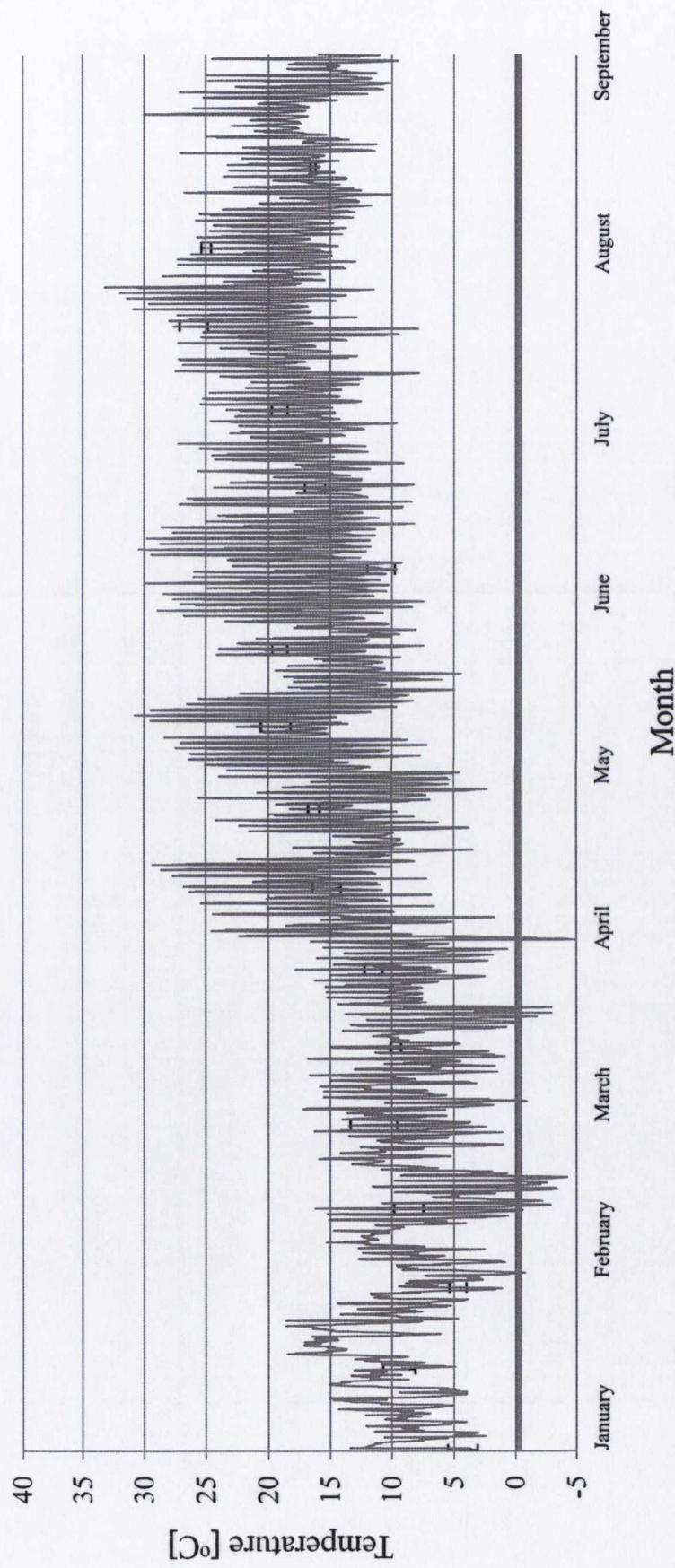


Figure 3.3: Average hourly air temperature (°C) recorded in 2009 for the control microcosms, data is averaged across four replicates (n=4) and there was no statistically significant difference between the replicates ($P < 0.05$), Bars represent the standard error in recorded temperature at two week intervals

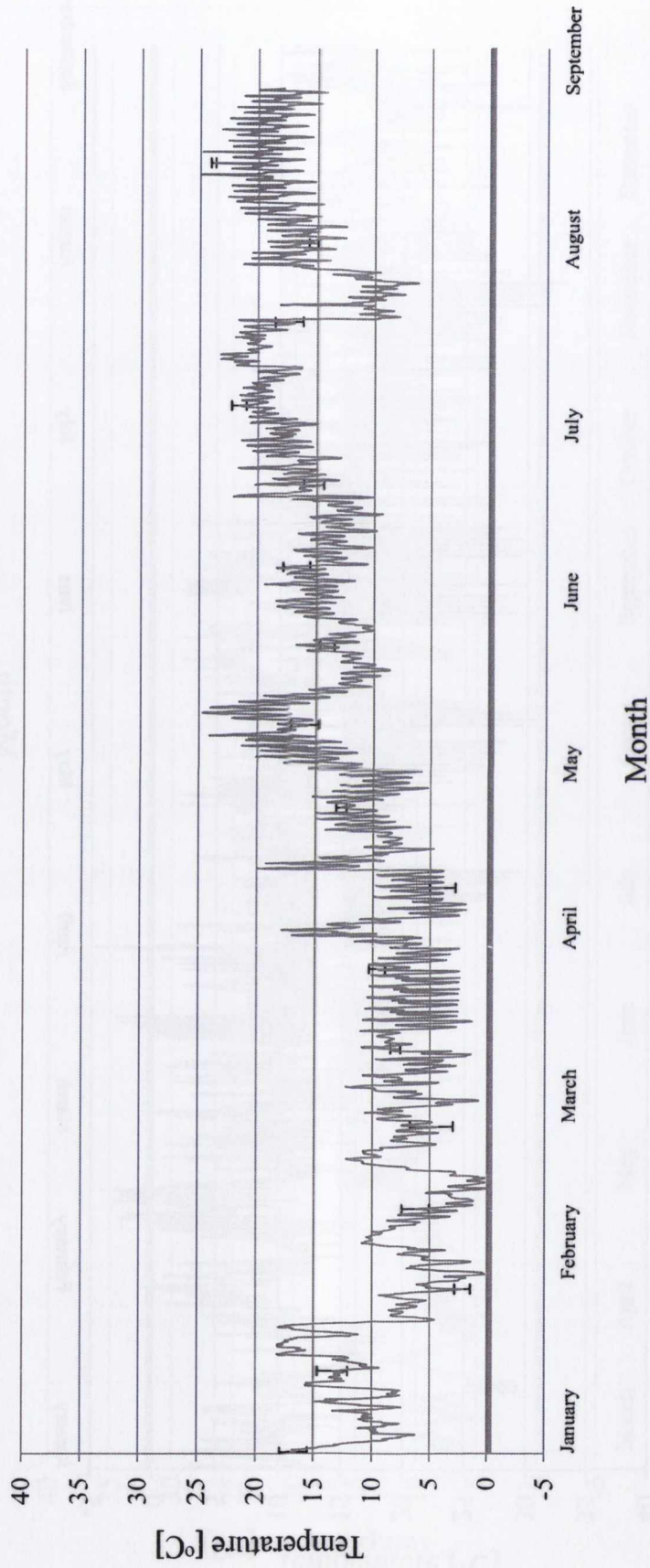


Figure 3.4: Average hourly soil temperature (°C) recorded in 2009 for the control microcosms, data is averaged across four replicates (n=4) and there was no statistically significant difference between the replicates ($P < 0.05$). Bars represent the standard error in recorded temperature at two week intervals

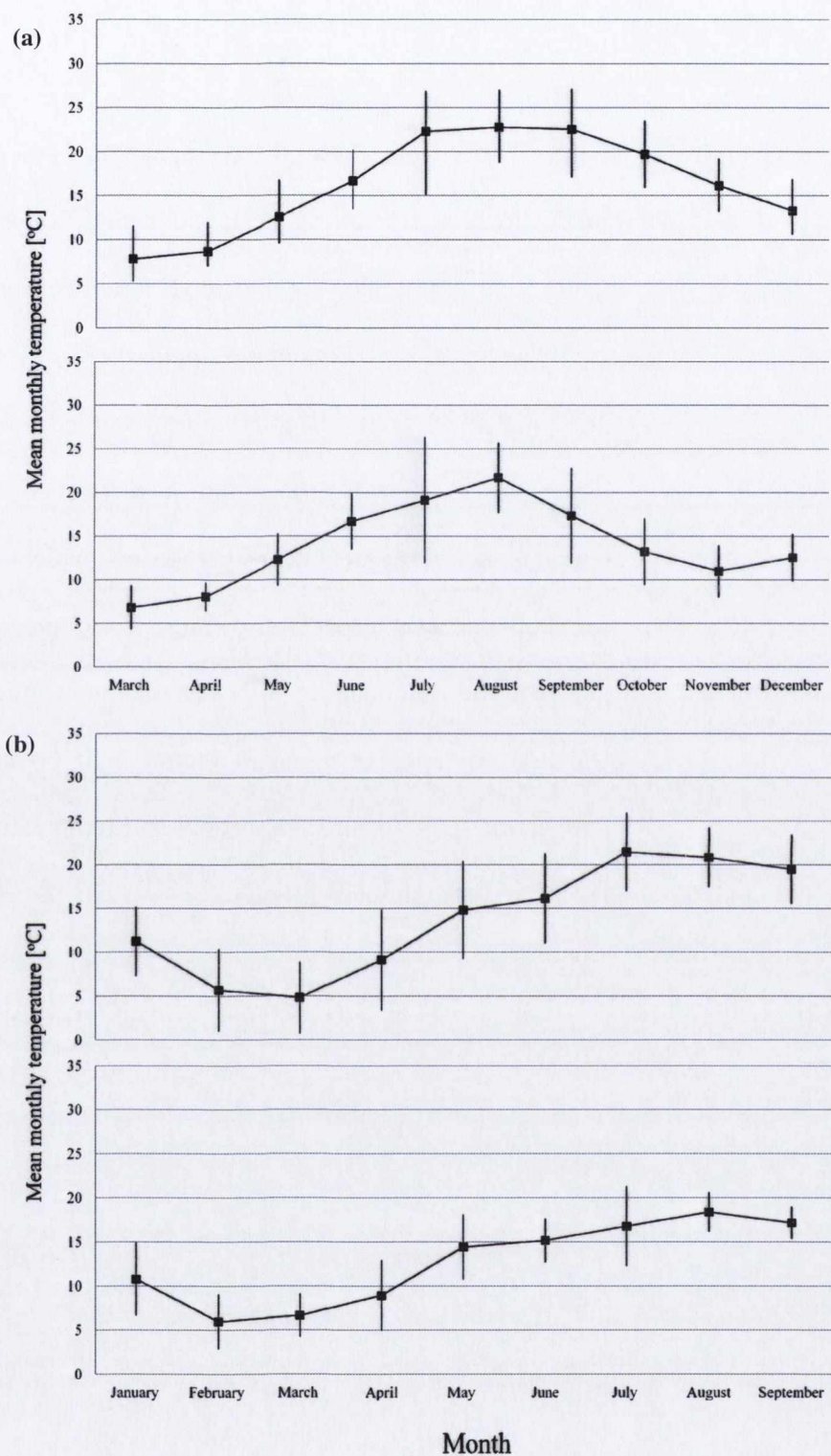


Figure 3.5: Monthly mean and standard deviation of the range of values of air and soil temperature at 5 cm depth recorded in 2008 (a) and for 2009 (b) recorded in the control microcosms

3.2.2 Treatment microcosms

Figure 3.6 to 3.9 represent the average air and soil temperatures recorded in the treatment microcosms in 2008 and 2009. As with the control values, no statistically significant differences were found between the replicates ($n=4$, $P<0.05$) and the standard error in two week intervals are presented due to the number of values recorded.

Over the two years we found a difference in the annual mean temperatures of the treatment microcosms, which were 16.8°C and 15°C for 2008 and 2009 respectively. Figure 3.10 represents the monthly mean air and soil temperature for the treatment microcosms, with their standard deviation is given in Figure 3.10 (a) and (b) and the same temperature pattern for both air and soil temperatures were observed as for the control microcosms.

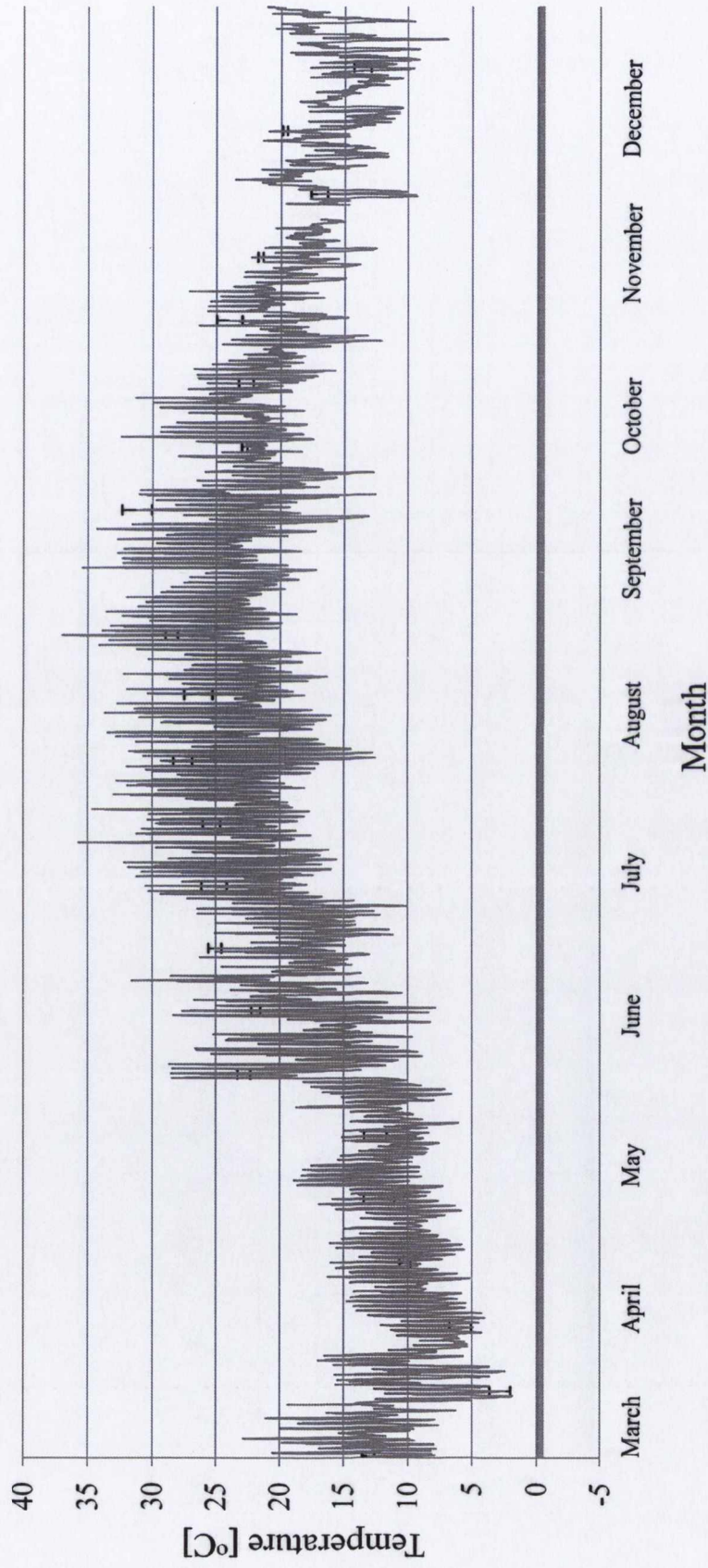


Figure 3.6: Average hourly air temperature (° C) recorded in 2008 for the treatment microcosms, data is averaged across four replicates(n=4) and there was no statistically significant difference between the replicates ($P<0.05$), Bars represent the standard error in recorded temperature at two week intervals

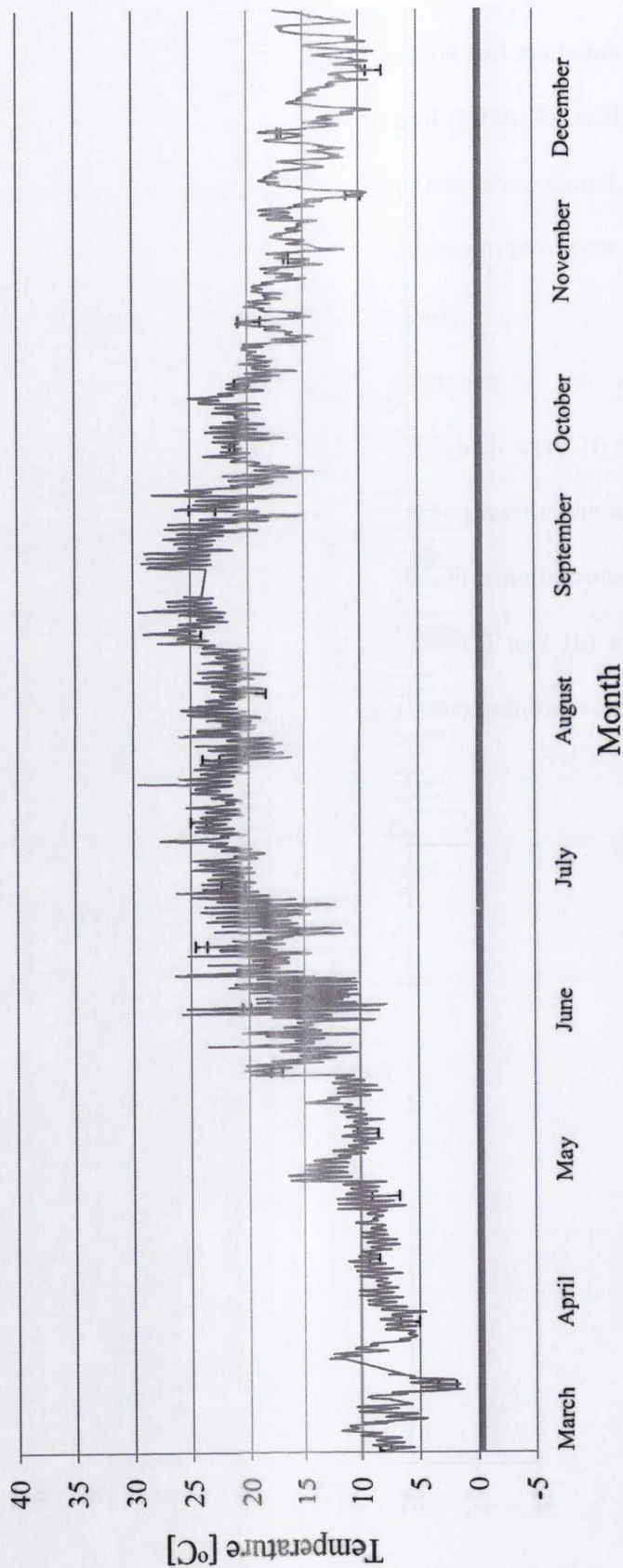


Figure 3.7: Average hourly soil temperature (°C) recorded in 2008 for the treatment microcosms, data is averaged across four replicates (n=4) and there was no statistically significant difference between the replicates ($P < 0.05$). Bars represent the standard error in recorded temperature at two week intervals

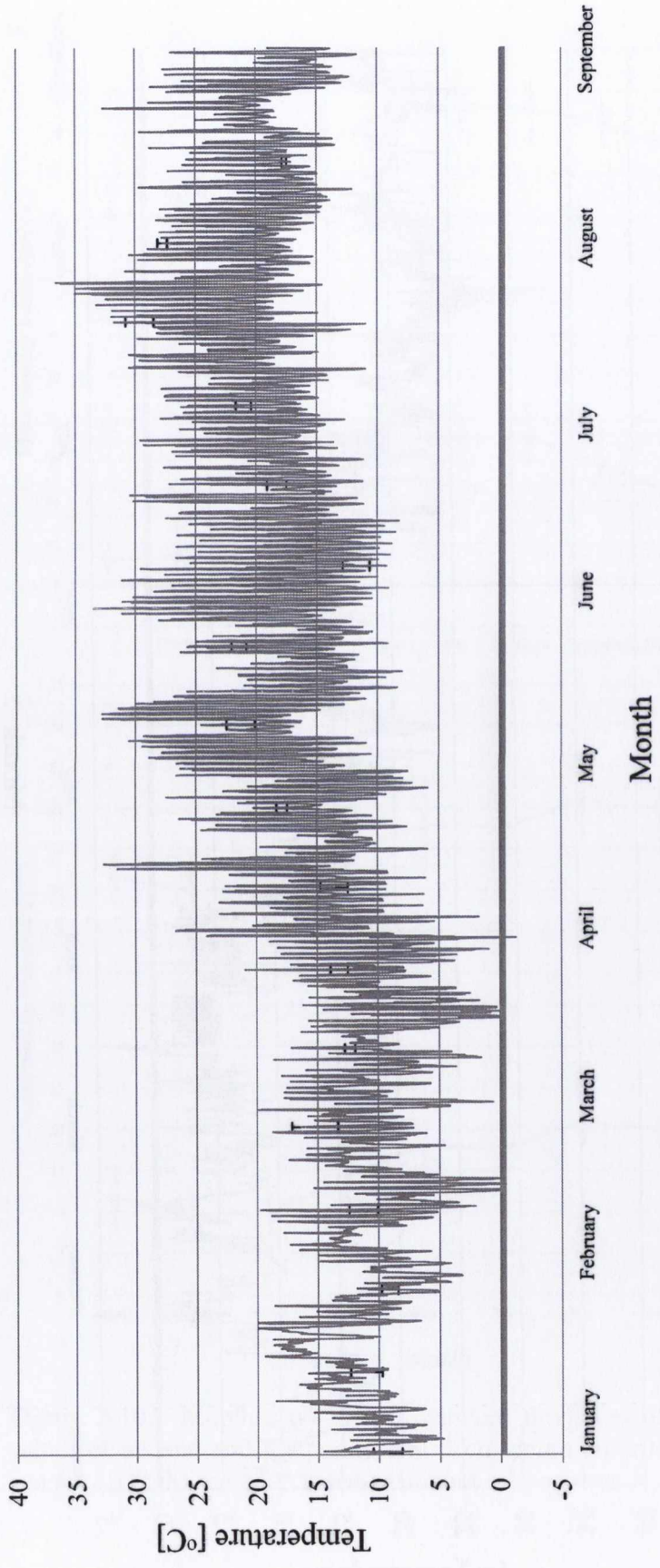


Figure 3.8: Average hourly air temperature (°C) recorded in 2009 for the treatment microcosms, data is averaged across four replicates (n=4) and there was no statistically significant difference between the replicates ($P<0.05$), Bars represent the standard error in recorded temperature at two week intervals

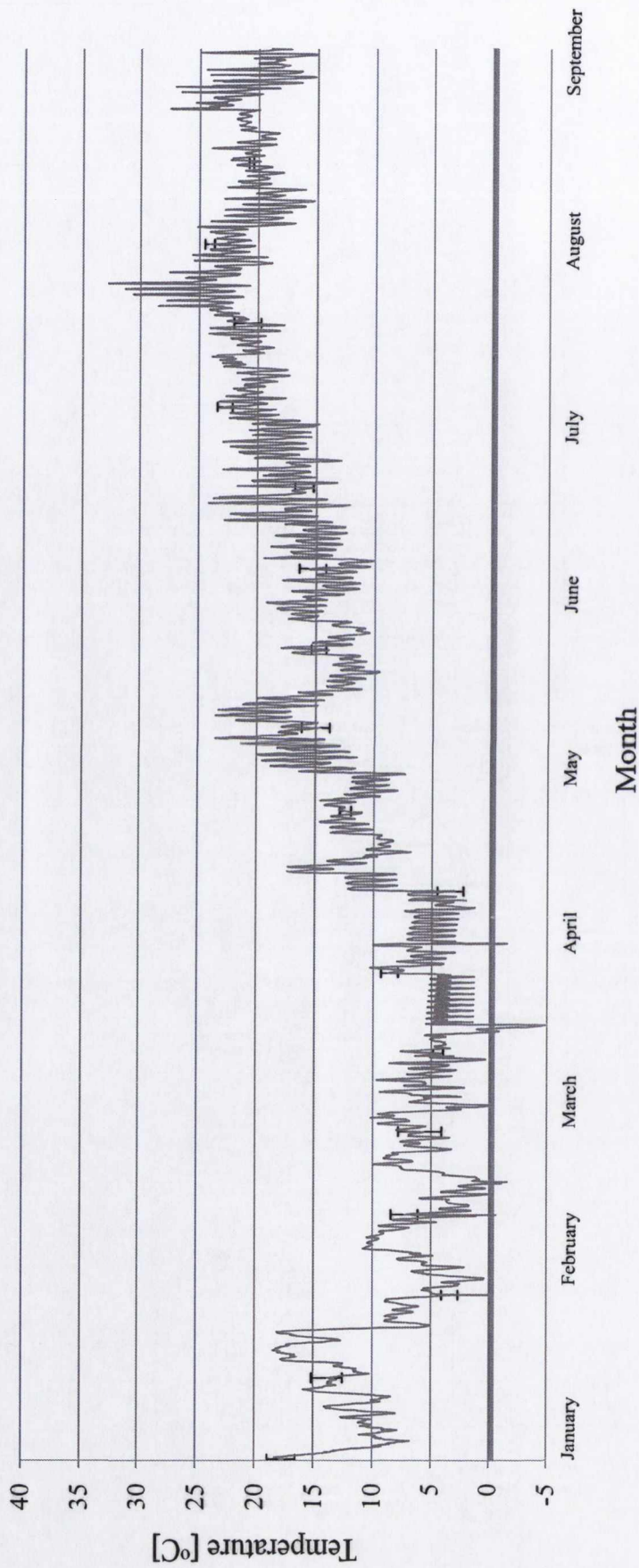


Figure 3.9: Average hourly soil temperature (°C) recorded in 2009 for the treatment microcosms, data is averaged across four replicates (n=4) and there was no statistically significant difference between the replicates ($P < 0.05$). Bars represent the standard error in recorded temperature at two week intervals

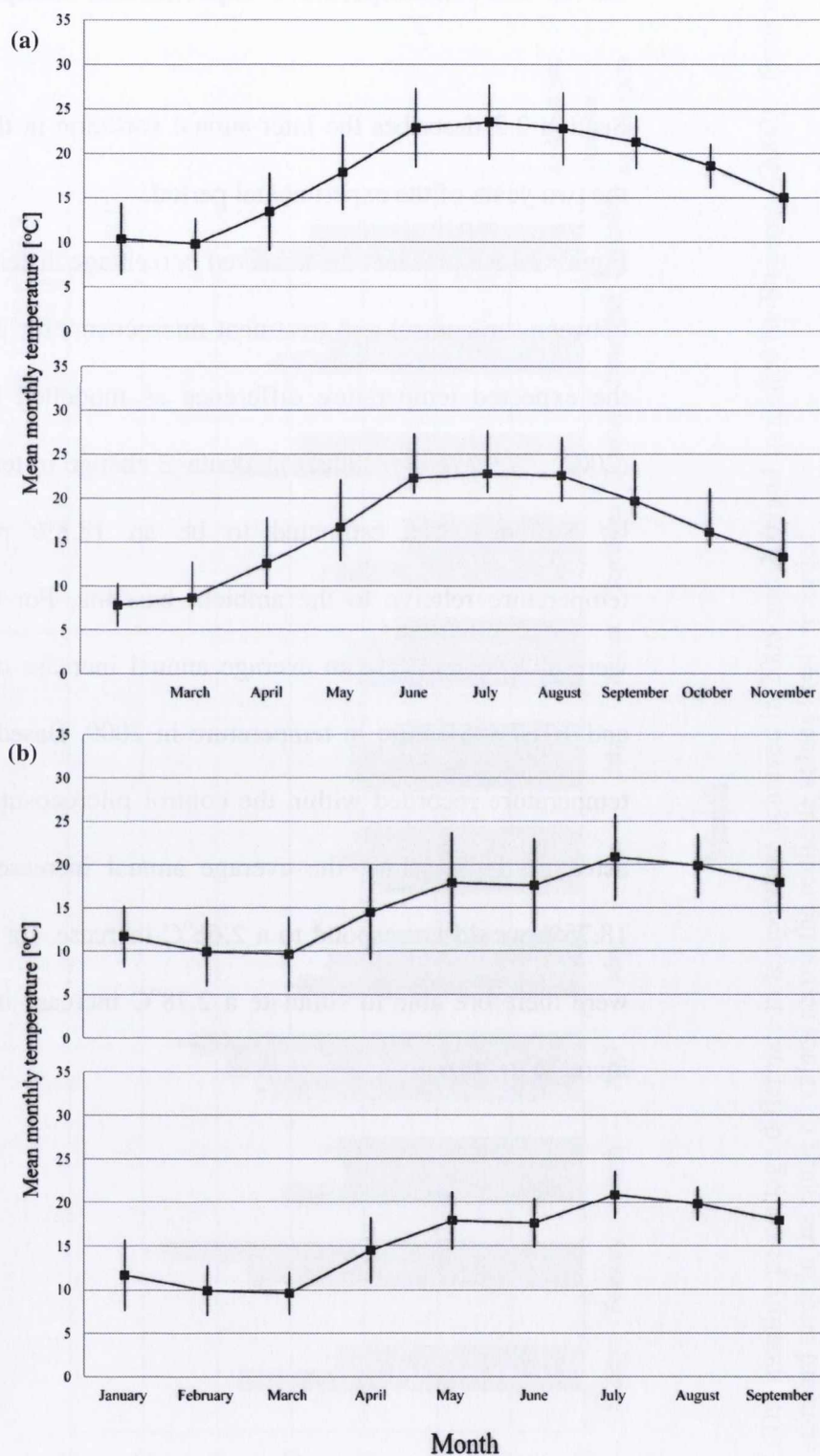


Figure 3.10: Monthly mean and standard deviation of the range of values of air and soil temperature at 5 cm depth recorded in 2008 (a) and for 2009 (b) recorded in the treatment microcosms

3.3 Air and soil temperature: experimental manipulation

Section 3.2 describes the inter-annual variation in the temperature over the two years of the experimental period.

Figure 3.11 represents the achieved percentage difference in temperature between the control and treatment microcosms for 2008, 2009 and also the expected temperature difference as modelled by Sweeney *et al.*, (2002). The average annual percentage change in temperature modelled by Sweeney was estimated to be an 18.8% percent increase in temperature relative to the ambient baseline. For this experiment we were able to replicate an average annual increase of 19.034% in 2008 and 16.67% increase in temperature in 2009. Based on the average air temperature recorded within the control microcosm, which in essences acted as the baseline, the average annual increase in temperature of 18.75% would correspond to a 2.66°C increase, for this experiment we were therefore able to simulate a 2.78°C increase in 2008 and a 2.3°C increase in 2009.

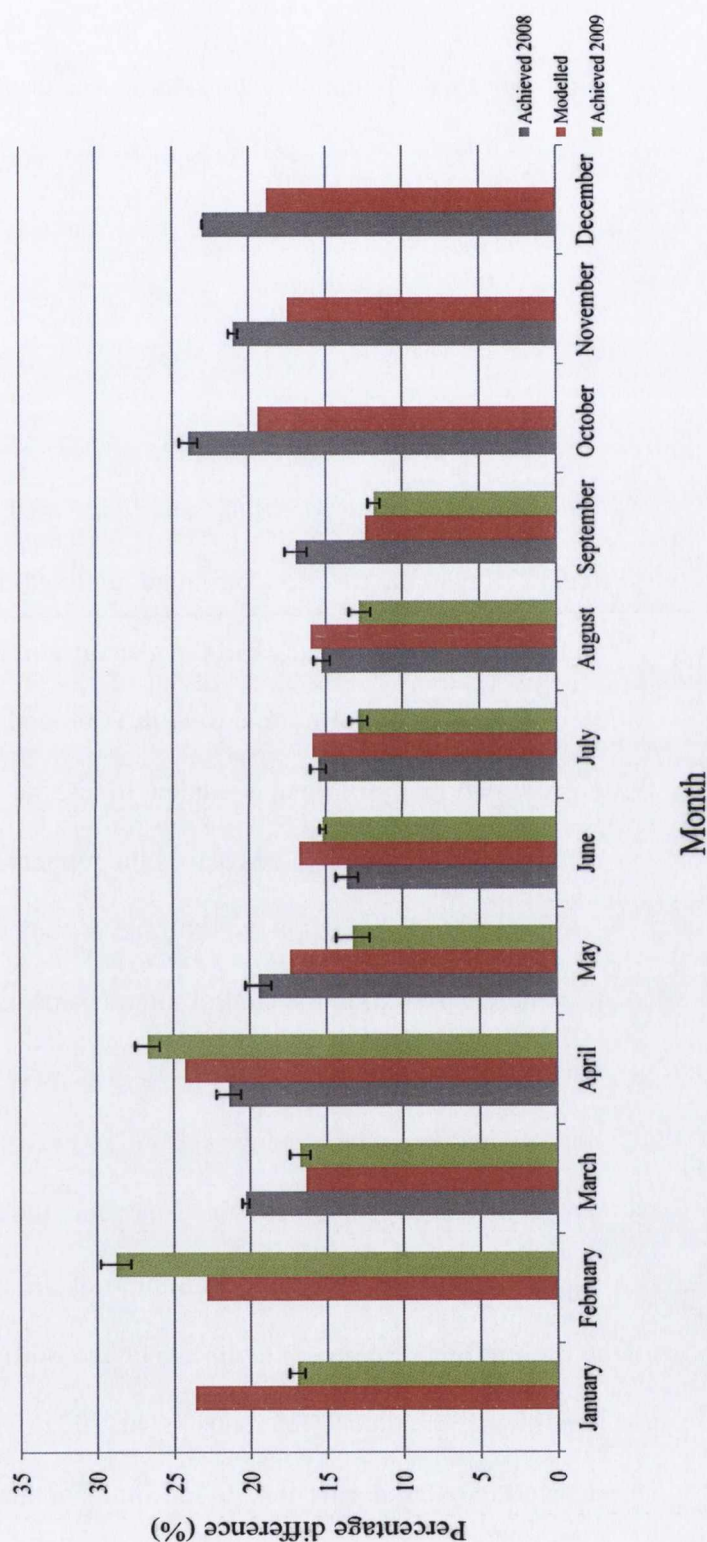


Figure 3.11: The monthly percentage difference in temperature achieved in 2008 and 2009 and modelled by Sweeney (2002). Error bars represent the standard error in the range of values across the replicate values ($n=4$) recorded.

3.4 Soil moisture

Soil moisture content in each microcosm was measured on an hourly basis by TDR (Campbell Scientific, see above section). Unlike for temperature, where on a monthly basis there is an increase temperature levels, for precipitation depending on the month levels can either increase relative to the baseline or decrease. Once information on the soil moisture contents was downloaded from the Oak Park research site, we repeated the data processing and data analysis steps as done for temperature data (Section 3.3) and outlined in chapter 2. Therefore figures 3.12 and 3.13 represent the average soil moisture contents for the treatment and control microcosms in 2008 and 2009. Across all values an ANOVA analysis was undertaken to test that there was no significant difference in recorded values across the replicates ($n = 4$) and none were found ($P < 0.05$). For 2008 the average annual volumetric soil moisture content (figure 4.8) in the control microcosms was $0.31 \text{ m}^3/\text{m}^3$ compared with a soil moisture content of $0.28 \text{ m}^3/\text{m}^3$ in the treatment microcosms. Soil moisture contents ranged from a maximum of $0.47 \text{ m}^3/\text{m}^3$ in November and $0.4 \text{ m}^3/\text{m}^3$ in June for the control and treatment microcosms respectively to a minimum of $0.2 \text{ m}^3/\text{m}^3$ in April and $0.09 \text{ m}^3/\text{m}^3$ in July. Figure 4.9 represents the soil moisture values of the control and treatment microcosms in 2009. The average annual soil moisture content during this period in the control microcosms was $0.33 \text{ m}^3/\text{m}^3$ with values ranging from a maximum of $0.43 \text{ m}^3/\text{m}^3$ in August of $0.4 \text{ m}^3/\text{m}^3$ for to a minimum of $0.23 \text{ m}^3/\text{m}^3$. For the treatment

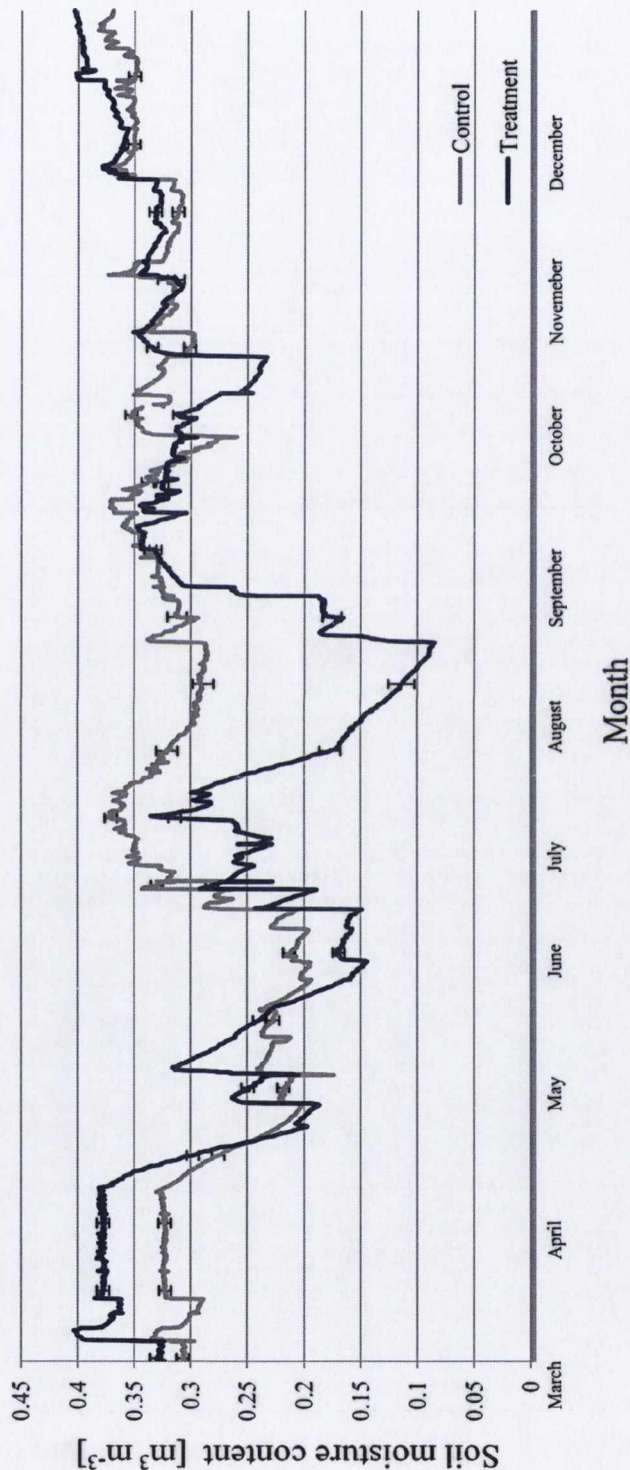


Figure 3.12: Average hourly soil moisture content (m^3/m^3) recorded in 2008 for the control and treatment microcosms, data is averaged across four replicates ($n=4$) and there was no statistically significant difference between the replicates ($P<0.05$). Bars represent the standard error in recorded temperature at two week intervals

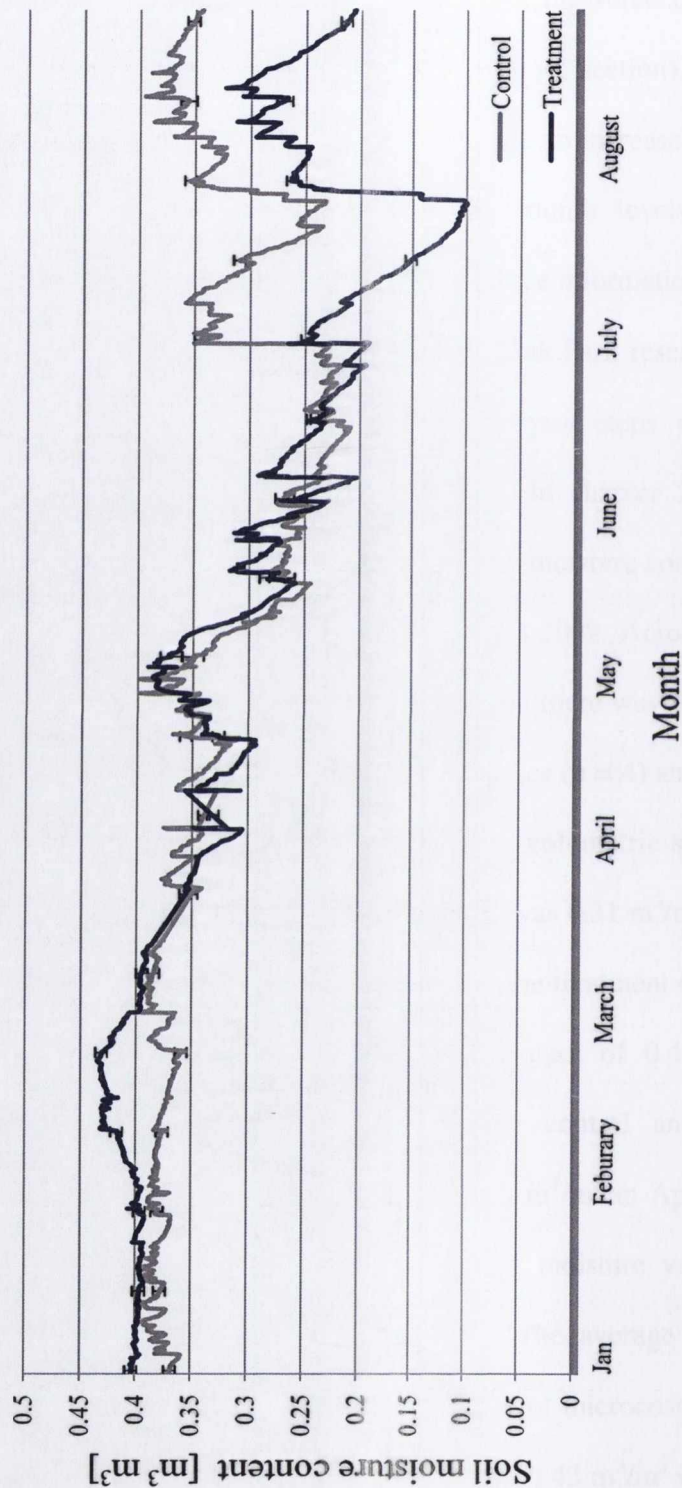


Figure 3.13: Average hourly soil moisture content (m^3/m^3) recorded in 2008 for the control and treatment microcosms, data is averaged across four replicates ($n=4$) and there was no statistically significant difference between the replicates ($P<0.05$), Bars represent the standard error in recorded temperature at two week intervals

microcosms the average annual soil moisture content was $0.30 \text{ m}^3/\text{m}^3$ where values ranged from $0.1 \text{ m}^3/\text{m}^3$ for in July to $0.43 \text{ m}^3/\text{m}^3$ in April. Figure 3.14 represents the achieved percentage difference in soil moisture between the control and treatment microcosms for 2008, 2009 and also the expected based on model estimates by Sweeney *et al*, (2002). As stated previously the percentage difference can either be a positive or negative, where for example in July there is an approximately 50% decrease in the level of precipitation whereas for August there is an expected 30% increase in precipitation relative to the baseline. On an annual basis, Sweeney (2002) predicted through modelling a 11.5% decrease in the level of precipitation. For this experiment in 2008 we replicated a 9% and 8.69% decrease in precipitation compared to the ambient baseline for 2008 and 2009 respectively.

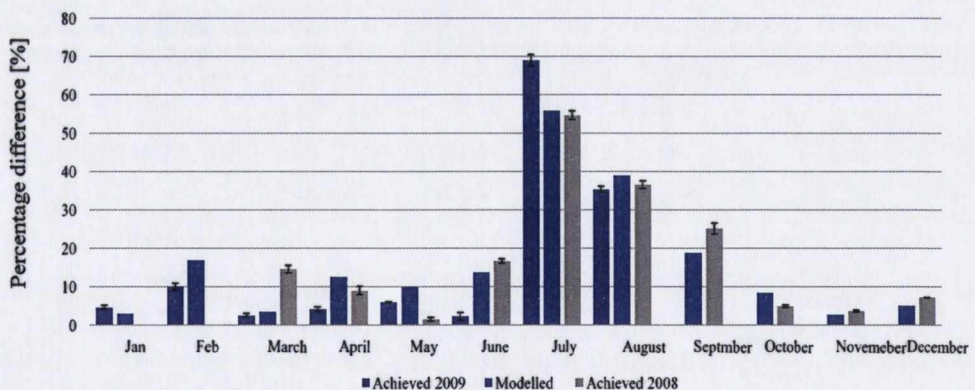


Figure 3.14: The monthly percentage difference in precipitation achieved in 2008 and 2009 and modelled by Sweeney (2002). Error bars represent the standard error in the range of values across the replicate values (n=4) recorded.

3.5 Solar radiation

Solar radiation was measured on an hourly basis for 2008 and 2009, both inside the microcosms and also externally. In each case there is a clear annual pattern, where maximum values were recorded in the summer months and lower levels recorded in winter (Figure 3.15 (a) and (b)).

The average annual solar radiation measured at the experimental site was 0.201 and 0.175 W m^{-2} for 2008 and 2009 respectively, representing a 13% reduction in the overall light levels recorded over the experimental period.

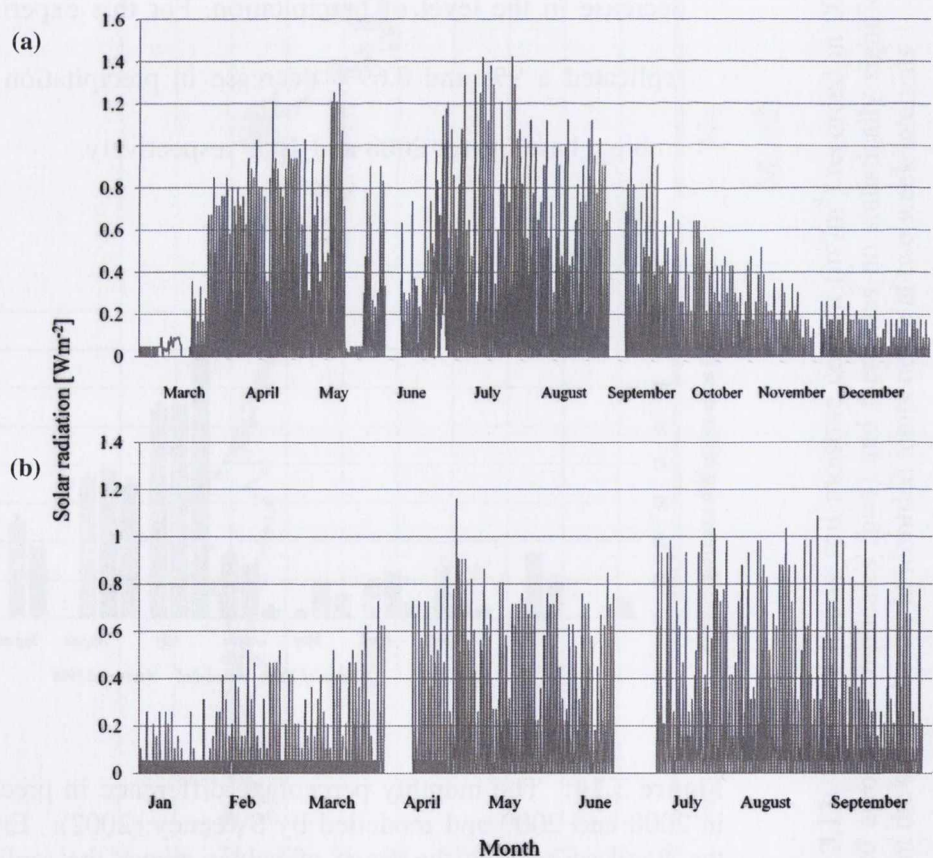


Figure 3.15: Hourly solar radiation (W m^{-2}) recorded at the Oak Park research centre for (a) 2008 and (b) 2009)

Chapter 4:

4: The measurement and partition of Net ecosystem exchange into gross primary production and respiration

4.1 Data Analysis and gap filling analysis

Over the course of the experimental period, reference and analysis and their differential CO₂ concentrations were collected from each microcosm for seven minutes each hour, with the exception of chamber 8 in which CO₂ concentrations were measured for 10 minutes each hour. The final minute of each hour was used as an automatic zero calibration of the IRGA. .

For each chamber, the initial two minutes of readings were discarded to avoid any possible interference from the previous chamber, and the hourly CO₂ fluxes were based on the average over the measurement period. There were four monoliths per treatment so that the CO₂ fluxes are based on the average of 4 microcosms. Additionally data was discarded between 12pm to 3pm on days when crop height and soil respiration was measured or harvests were made. For each microcosm approximately 1176 measurements of CO₂ concentrations per week were made or 61,153 per year. When all lost data collection periods were accounted for, including the dates given in section 3.1, approximately 70 per cent of the data collected was used in the final CO₂ flux analysis. Over the course of the experimental period data was lost due to power outages and data was also discarded due to potential interference in the IRGA when the automated system switched between the chamber

measured (Section 2.4.1) and also interference when supplemental measurements were made as the microcosms were opened. In total per microcosm 47,040 and 42,336 values of CO₂ were recorded in 2008 and 2009 per microcosm. Of these 14,840 and 14,616 values were either lost or discarded in 2008 and 2009 respectively however only missing data due to power outages and chamber interference due to the supplemental measurements was gap filled

Sections 2.4.5 and 2.5 outlines in detail the steps taken to gap fill and process the downloaded data from the IRGA, however in order to effectively fill gaps a number of steps were followed including:

- a)** To account for the changes in the seasonal response of NEE, GPP and R to temperature and precipitation only data immediately preceding the gap in the data was used.
- b)** To account for the different relationship between GPP and R with temperature and precipitation different day and night gap filling criteria were used. Therefore daytime CO₂ fluxes were a function of the incoming PAR radiation (Klumpp *et al.*, 2007) and night time and daytime soil respiration rates were calculated as a function of soil temperature (Amthor, 1989).

Values collected	2008	2009
Per hour	7	7
Per day	168	168
Per week	1176	1176
Per month	4707	4707
<i>Total in year</i>	47040	42336
Values discarded due to (per year):		
IRGA interference	13440	12096
Supplemental measurement	560	2016
Power outages	840	504
<i>Total</i>	14840	14616
Percentage of total discarded	31.5	34.5

Table 4.1: CO₂ concentration values that was collected and discarded per year due to: interference or power outages per microcosm in 2008 and 2009.

4.1.1 Daytime NEE gap filling

In the periods immediately preceding the gaps in the data we fitted measured daytime NEE with solar radiations values and the resulting equations were then used with the solar radiations collected from a site adjacent to the experimental set up. Figures 4.1 and 4.2 shows an example of the light response curves established for the three days preceding April 1st for the treatment and control microcosms, whose relationships were used to provide an estimate of the ‘missing’ data.

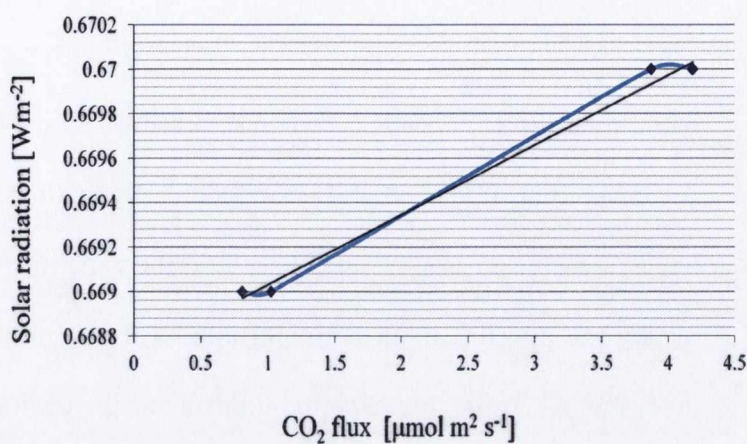


Figure 4.1: The relationship between CO₂ fluxes and measured PAR in the treatment microcosms recorded on 15th April 2008. $R^2 = 0.9626$

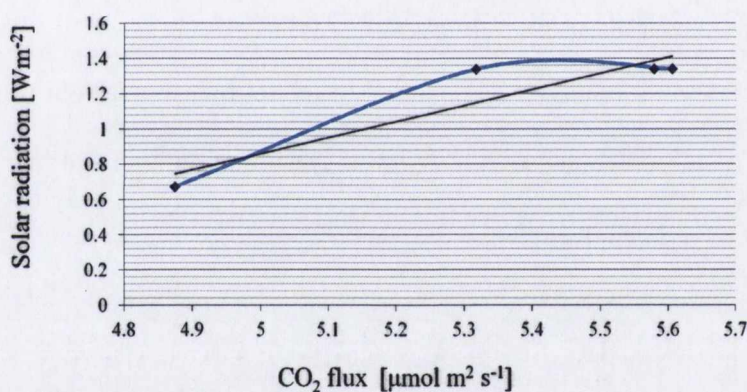


Figure 4.2: The relationship between CO₂ fluxes and measured PAR in the control microcosms on March 30th 2009. R^2 value = 0.8633

4.1.2 Night time NEE gap filling

Night time gap filling was based on the established relationship between soil respiration rates and soil temperature. Night time soil temperature values were taken from a site adjacent to the experimental site and used to provide an estimate of the night time NEE in both the treatment and control microcosms. In the period immediately preceding the 'gap' in the data a relationship between the measured night-time NEE and soil temperatures were established and the resulting equation was used with soil temperatures values recorded in an adjacent site to provide an estimate of night time NEE. To test the accuracy of this method we then used the derived equations to model measured night time NEE, this step was repeated within both the treatment and control microcosms (Figures 4.3 and 4.4).

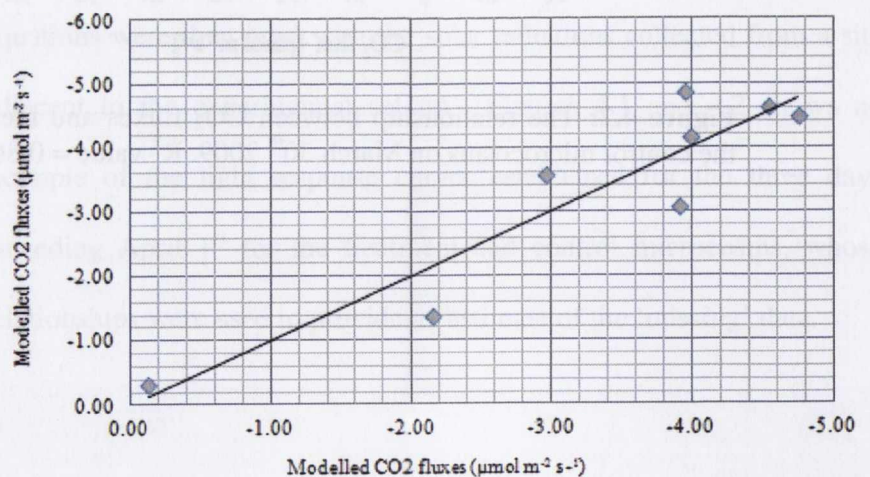


Figure 4.3: The relationship between night time CO₂ fluxes and measured soil temperatures in the control microcosms on March 30th. $R^2 = 0.80$

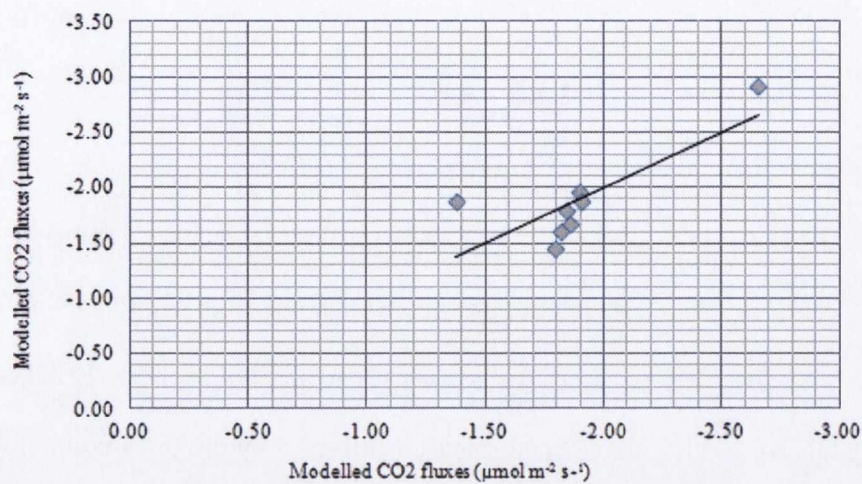


Figure 4.4: The relationship between night time CO₂ fluxes and measured soil temperatures in the treatment microcosms on March 30th. $R^2 = 0.63$

4.2. CO₂ fluxes

4.2.1 *Daily fluxes*

The pattern of CO₂ uptake and release follows a typical daily pattern, where at night time CO₂ is released, due to soil and plant respiration, and leads to a loss of CO₂ to the atmosphere. However the time course of uptake and release is affected by the three main climatic drivers of the C budget: temperature, precipitation and PAR levels, which vary during the year and in addition management events such as harvesting. Figures 4.5 to 4.8 represent the average hourly CO₂ flux calculated across the 4 replicate microcosms, where there was no statistically significant difference between them ($P < 0.05$), with the standard deviation in CO₂ values recorded for each hour across the month graphed. For the spring months in 2008 the peak CO₂ flux in recorded in the treatment microcosms was calculated as approximately 10 $\mu\text{mol}/\text{m}^2/\text{s}$ and for the control microcosm was 5 $\mu\text{mol}/\text{m}^2/\text{s}$. In 2009 the peak CO₂ flux was calculated as 5 and 4 $\mu\text{mol}/\text{m}^2/\text{s}$ in the treatment and control microcosms respectively. In 2008 and 2009 the average daily temperature in the control microcosm was recorded at 4.5 and 5.7°C, and at 6.3 and 6.5°C for the treatment microcosms. The soil moisture content for the treatment and control microcosms for 2008 and 2009 was calculated as 0.37 $\text{m}^3 \text{ m}^{-3}$, 0.32 $\text{m}^3 \text{ m}^{-3}$, 0.37 $\text{m}^3 \text{ m}^{-3}$ and 0.322 $\text{m}^3 \text{ m}^{-3}$ respectively. During the summer months the maximum and minimum CO₂ flux recorded in the treatment and control microcosms at 15 and -8 $\mu\text{mol}/\text{m}^2/\text{s}$

in 2008. The average daily temperature in the control and treatment microcosm was recorded at 18.8 and 21.2°C in 2008 and 16.8 and 18.5°C in 2009. Average daily soil moisture was recorded as 0.21 and 0.344 m³ m⁻³ in the treatment and control microcosms in 2008 respectively and 0.29 and 0.36 m³ m⁻³ in 2009. For the autumn period, the maximum and minimum C flux was recorded in the control microcosm (figure 5.3) at 12 and -6 µmol/m²/s. Average daily temperatures in the treatment and control microcosm were recorded at 25.9 and 22.75°C in 2008 and 18.6 and 20.6°C in 2009. The soil moisture contents were recorded as 0.26 and 0.32 m³ m⁻³ in the treatment and control microcosms respectively in 2008 and 0.28 and 0.35 m³ m⁻³ in 2009. For the winter months, which are defined as December, January and February, the daily C flux is presented in figure 5.4. For both the treatment and control microcosms there is little difference in the C flux, with the peak C flux was recorded in the treatment microcosm at 2 µmol/m²/s. During this period the average daily temperature recorded in the treatment and control microcosms were 5.9 and 7.5°C respectively. Average soil moisture contents were recorded as 0.4 m³ m⁻³ in the treatment microcosms and 0.37 m³ m⁻³ in the control microcosms, during the winter months

As part of the experimental design of the project, which aims to reflect current management practices on Irish grasslands, during the growing period we harvested the biomass in each of the microcosms, which can alter the C budget of an ecosystem. Figures 4.9 and 4.10 (a and b) represent the measured (gray line) and gap filled (black line) average daily CO₂ flux for 2008 and 2009 for the treatment and control

microcosms with the harvest dates are indicated by arrows. Both figures highlight the impact the removal of biomass has on the productivity of the monocultures of *Lolium perenne*. In both 2008 and 2009, after the harvest events, as expected there is a sharp decline in NEE in both the treatment and control microcosms, and their respective ability to recover of the monocultures to recover in 2008 and 2009 is dependent on the climatic conditions. For example the average monthly temperature in the for the treatment microcosms for June and July in 2008 was recorded at 17.5 and 20.8°C, with the soil moisture content recorded as 0.30 m³ m⁻³ and 0.17 m³ m⁻³ respectively. Whereas the control microcosms the average monthly temperatures were 16.6°C in June and 18.5°C in July and the average soil moisture content was recorded at 0.24 m³ m⁻³ and 0.30 m³ m⁻³ for the same period, leading to a wetter soil status which will respire more. This means that despite lower GPP values, the treatment microcosms remain a sink of CO₂ due to lower soil respiration rates, however in the control microcosms the higher R rates after the biomass harvests mean that they become a sources of CO₂ during these months.

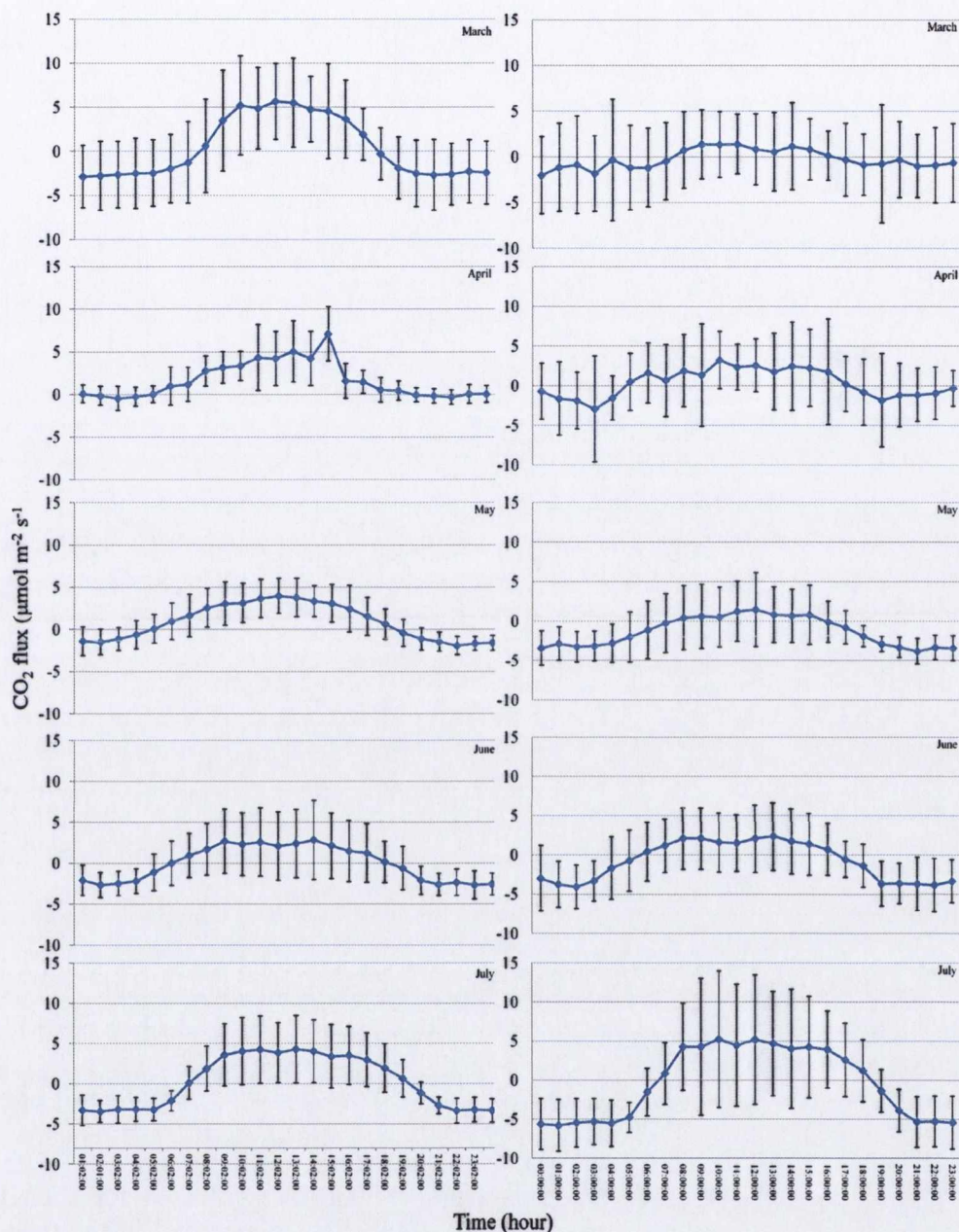


Figure 4.5: The average hourly CO₂ fluxes for each month with their standard deviation for 2008. Values recorded in the treatment microcosms are on the left, control values are on the right. Data are means of four different microcosms (n=4), and there was no statistically significant difference between the replicates ($P < 0.05$).

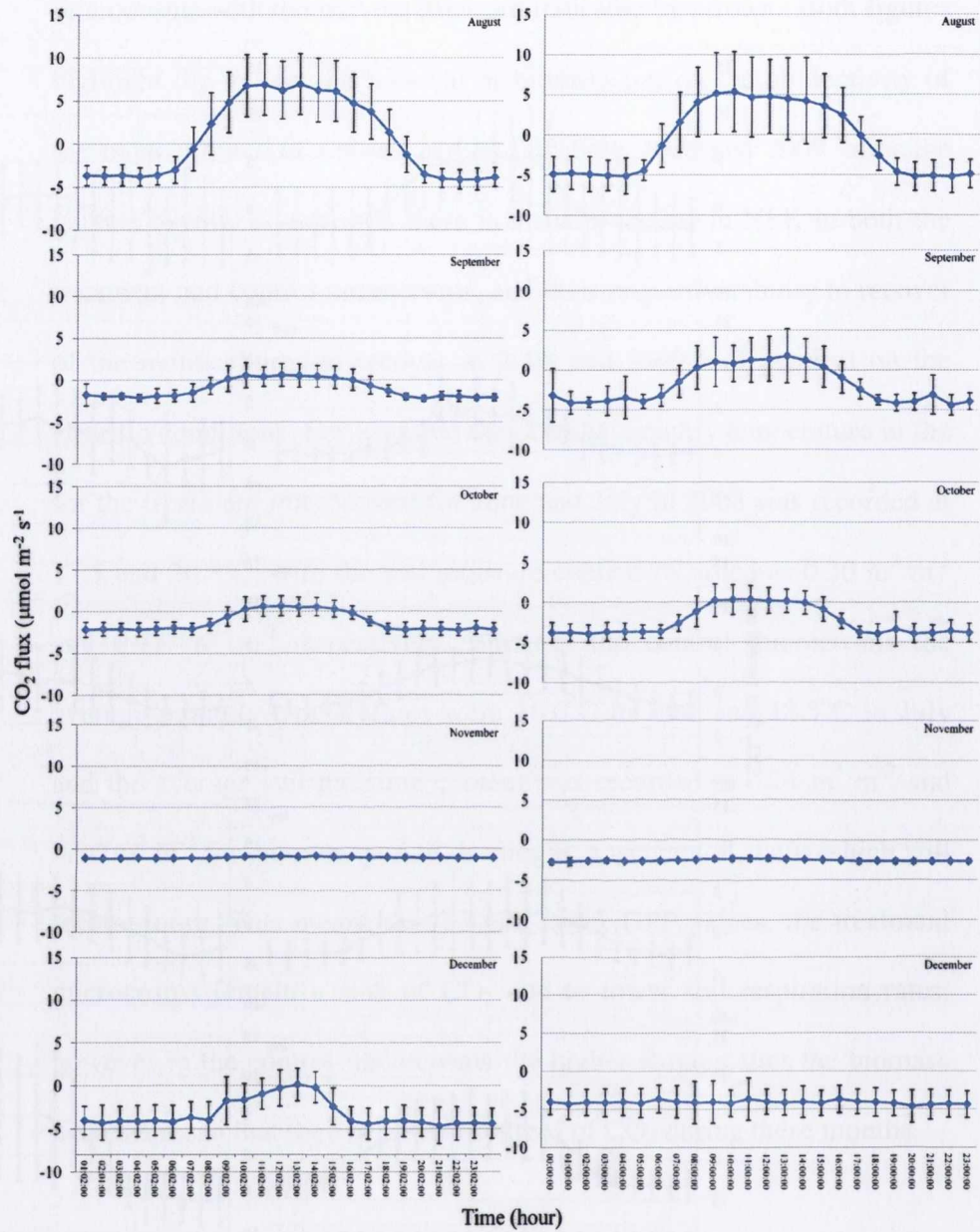


Figure 4.6: The average hourly CO₂ fluxes for each month with their standard deviation for 2008. Values recorded in the treatment microcosms are on the left, control values are on the right. Data are means of four different microcosms (n=4). and there was no statistically significant difference between the replicates ($P < 0.05$)

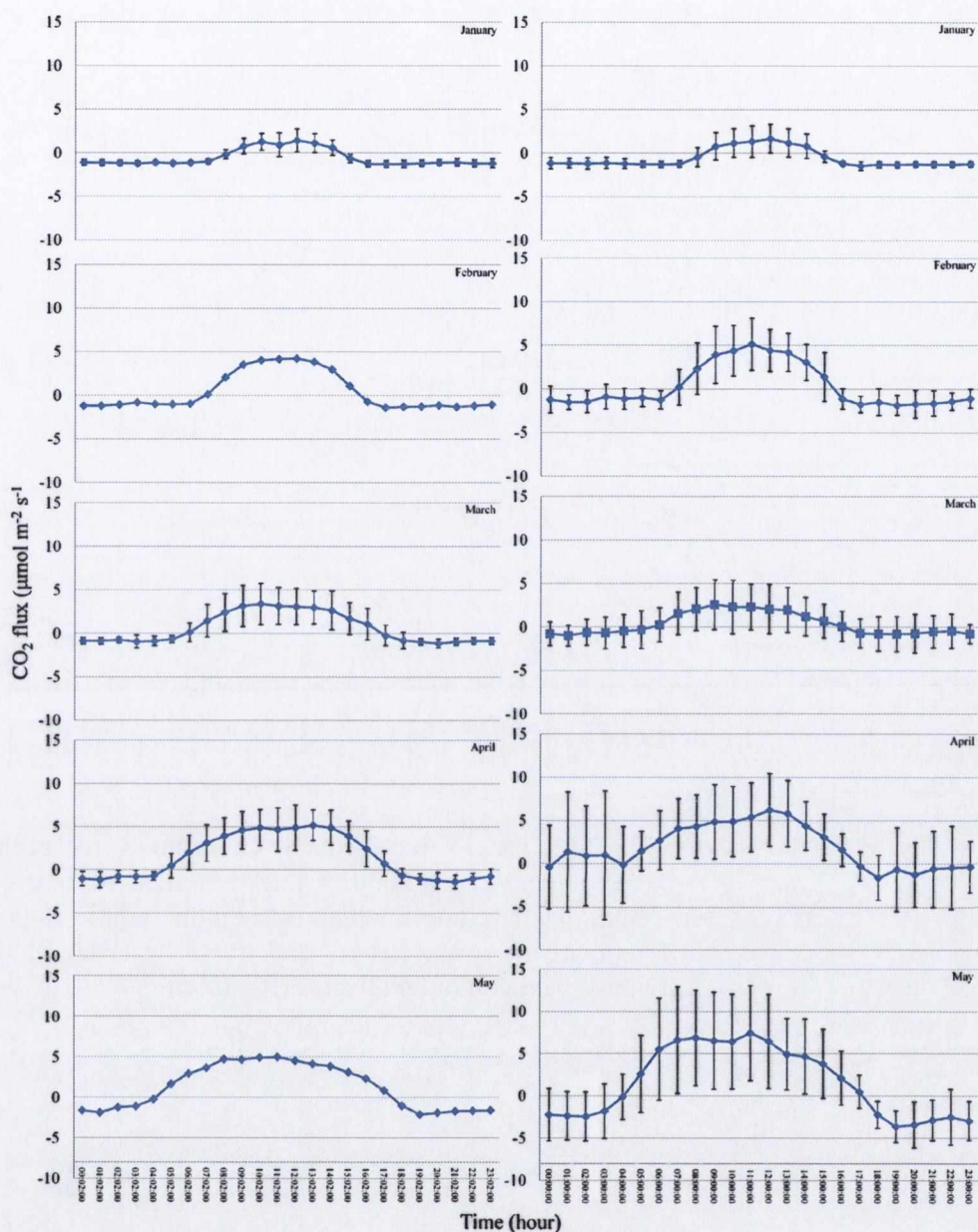


Figure 4.7: The average hourly CO₂ fluxes for each month with their standard deviation for 2009. Values recorded in the treatment microcosms are on the left, control values are on the right. Data are means of four different microcosms (n=4). and there was no statistically significant difference between the replicates ($P < 0.05$)

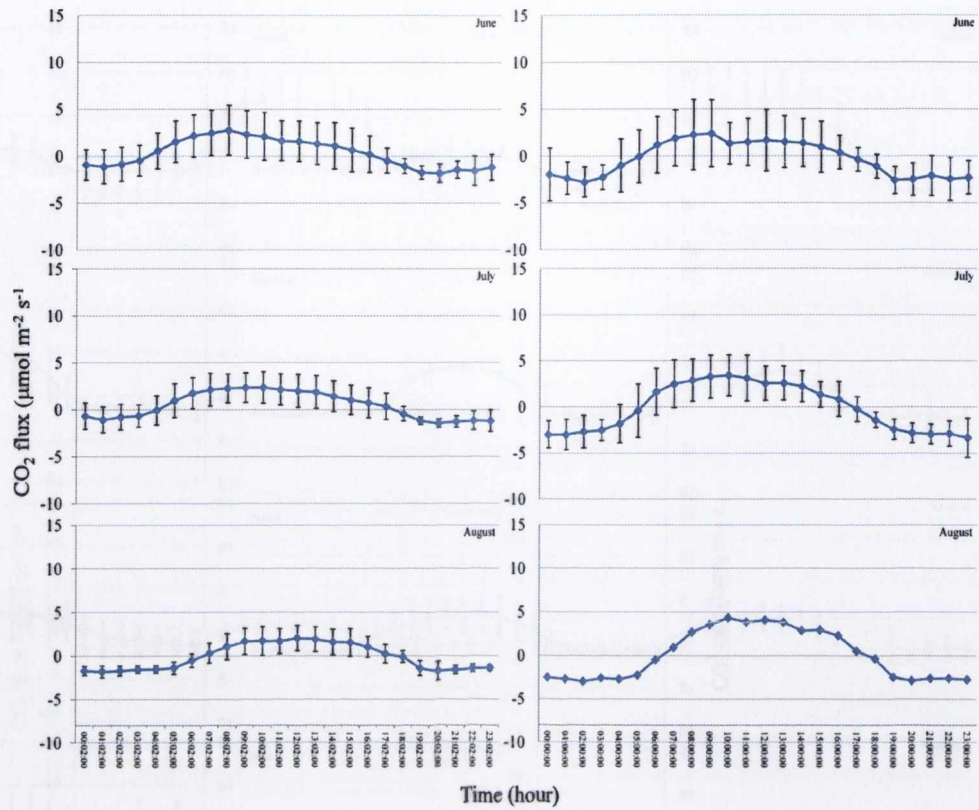


Figure 4.8: The average hourly CO₂ fluxes for each month with their standard deviation for 2009. Values recorded in the treatment microcosms are on the left, control values are on the right. Data are means of four different microcosms (n=4), and there was no statistically significant difference between the replicates ($P < 0.05$)

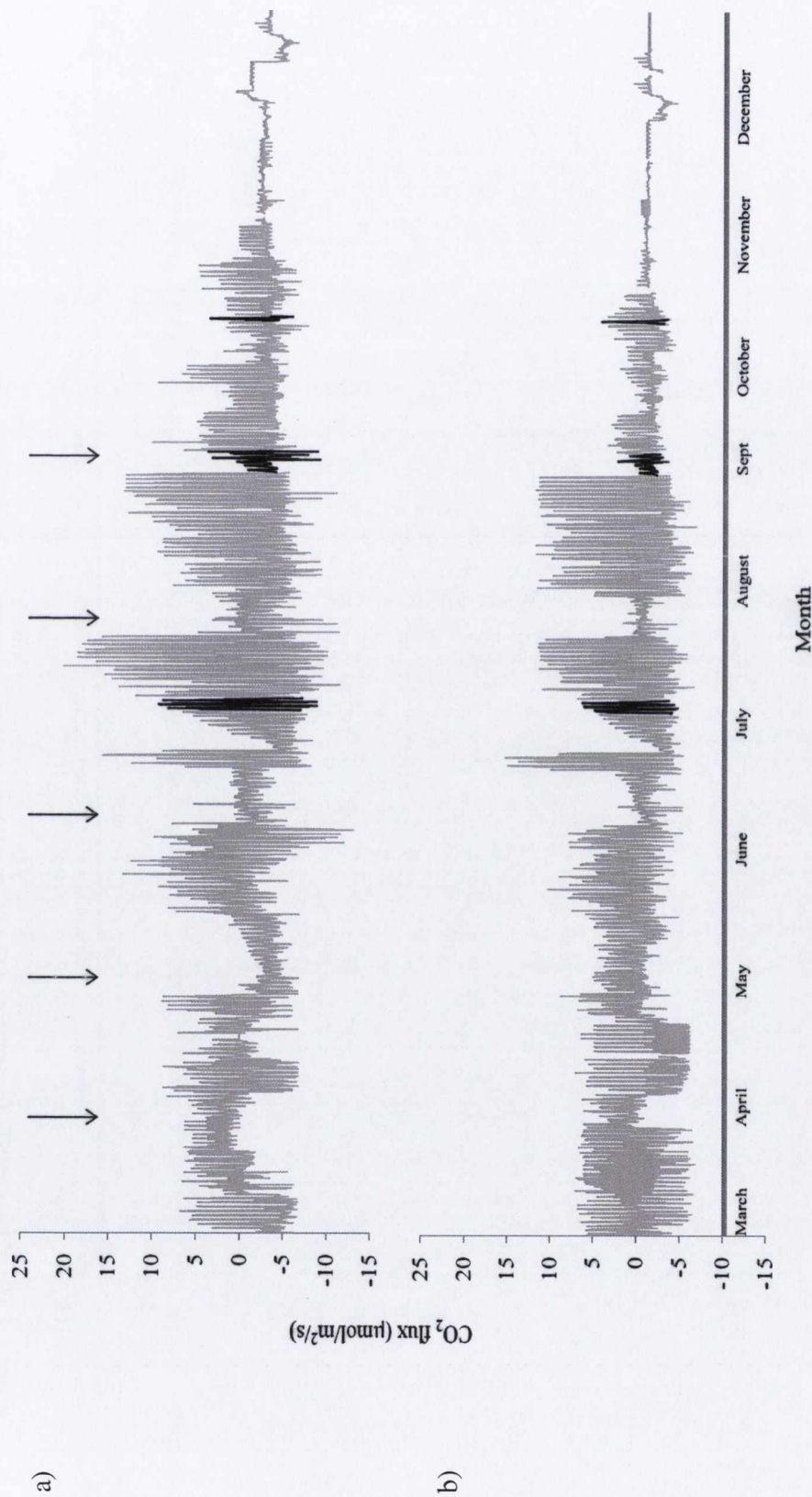


Figure 4.9: Daily NEE for control (a) and treatment (b) microcosms in 2008. Positive values denote carbon uptake, negative values denote carbon release, arrows indicate harvest events, grey line denotes measure values and black line indicates where data has been gap filled. Data are means averages across the four replicate microcosms ($n=4$), and there was no statistically significant difference between the replicates ($P < 0.05$)

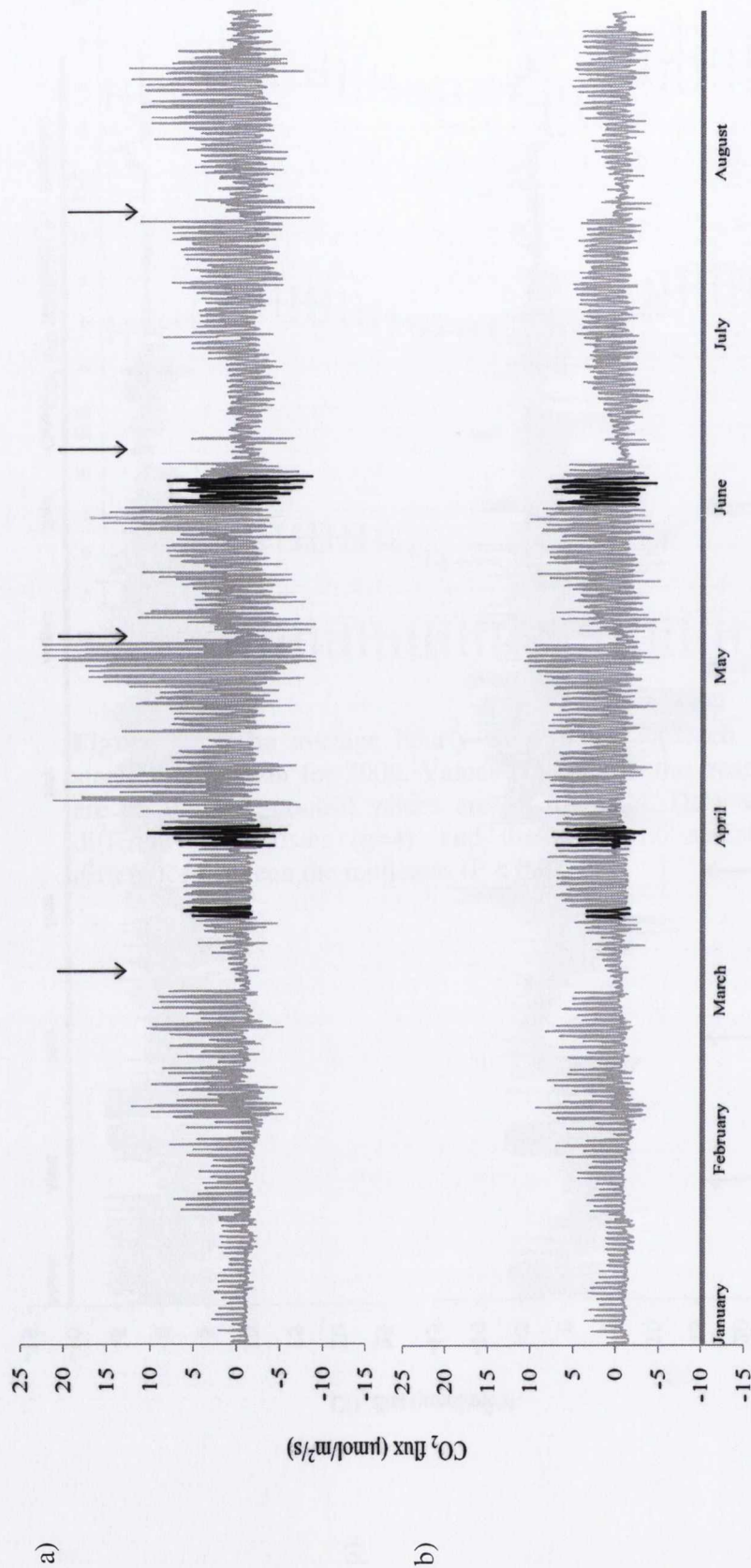


Figure 4.10: Daily NEE for control (a) and treatment (b) microcosms in 2009. Positive values denote carbon release, negative values denote carbon uptake, arrows indicate harvest events, grey line denotes measure values and black line indicates where data has been gap filled. Data are averages across the four replicate microcosms ($n=4$), and there was no statistically significant difference between the replicates ($P < 0.05$)

4.2.2: Soil respiration rates

Over the period of the experimental period daytime soil respiration measurements in each of the microcosms, with the fluxes averaged over the four replicates, for the treatment and control results were recorded. These measurements allowed us to:

- a) Determine the sensitivity of soil respiration, R , and also the respiration quotient, Q_{10}
- b) Evaluate the climatic variable that can act best as a predictor of daytime soil respiration which can in turn help to separate the components of NEE and help gap fill missing data.

We performed a sensitivity analysis by fitting the measured soil respiration rates (Figure 4.11 a and b) with the temperature according to the exponential equation (4.1) for both the treatment and control microcosms:

$$4.1: \quad R_{10} = ae^{bt}$$

Where R_h is the measured CO_2 efflux ($\mu\text{mol m}^{-2} \text{s}^{-1}$), t is the soil temperature and a is the basal respiration and b is the temperature sensitivity of soil CO_2 efflux. R_{10} was calculated as 0.285 and 0.213 for the treatment and control microcosms respectively. The Q_{10} value was then calculated according to the equation:

$$4.2: \quad Q_{10} = e^{10b}$$

The Q_{10} values were calculated as 2.3 and 2.59 for the treatment and control microcosms.

Soil respiration is strongly correlated with temperature (Lloyd and Taylor, 1994; Ise and Moorcroft, 2006; Fang and Moncrieff, 2001) and therefore it is commonly the only climatic variable used as a predictor of soil respiration rates. However more recently models of soil respiration rates are adjusted to account for soil moisture contents (Suseela *et al.*, 2012) to test which method acts as a better fit (temperature or a combination of temperature and precipitation) we fit a quadratic function with measure soil respiration rates and soil moistures contents:

$$4.3: \quad R_h = y_o + ax + bx^2$$

Where x is the volumetric moisture content in the top 10cm of the soil and y_o , a and b are constants (Figure 4.12, a and b). Based on the methods used by Mielnick and Dugas (2000), we combined the exponential and quadratic functions to predict soil CO_2 efflux. To determine which method acts as a better predictor of soil respiration rates we used the respective equations of the temperature and combined temperature and soil moisture function to model the measured soil respiration rates. We then performed a regression analysis of each

function with the measured values, to determine which function will act as a better predictor of soil respiration rates in the microcosms (Table 4.2)

	<i>Units</i>	<i>Measured ^a</i>	<i>Combined ^b</i>	<i>Temperature ^c</i>
<i>Mean</i>	$\mu\text{ mol m}^2\text{ s}^{-1}$	0.42	0.20	0.42
<i>Standard dev</i>	$\mu\text{ mol m}^2\text{ s}^{-1}$	0.18	0.17	0.21
<i>Maximum</i>	$\mu\text{ mol m}^2\text{ s}^{-1}$	0.82	0.65	1.00
<i>Minimum</i>	$\mu\text{ mol m}^2\text{ s}^{-1}$	0.09	0.05	0.22
<i>R² of regression</i>		-	0.56	0.66

Table 4.2: The table of results for the measured soil respiration rates (a) compared with the combined temperature and precipitation function (b) and the temperature function (c). Results of the mean, standard deviation, maximum and minimum recorded and modelled respiration rates and the r² of the regression analysis are given.

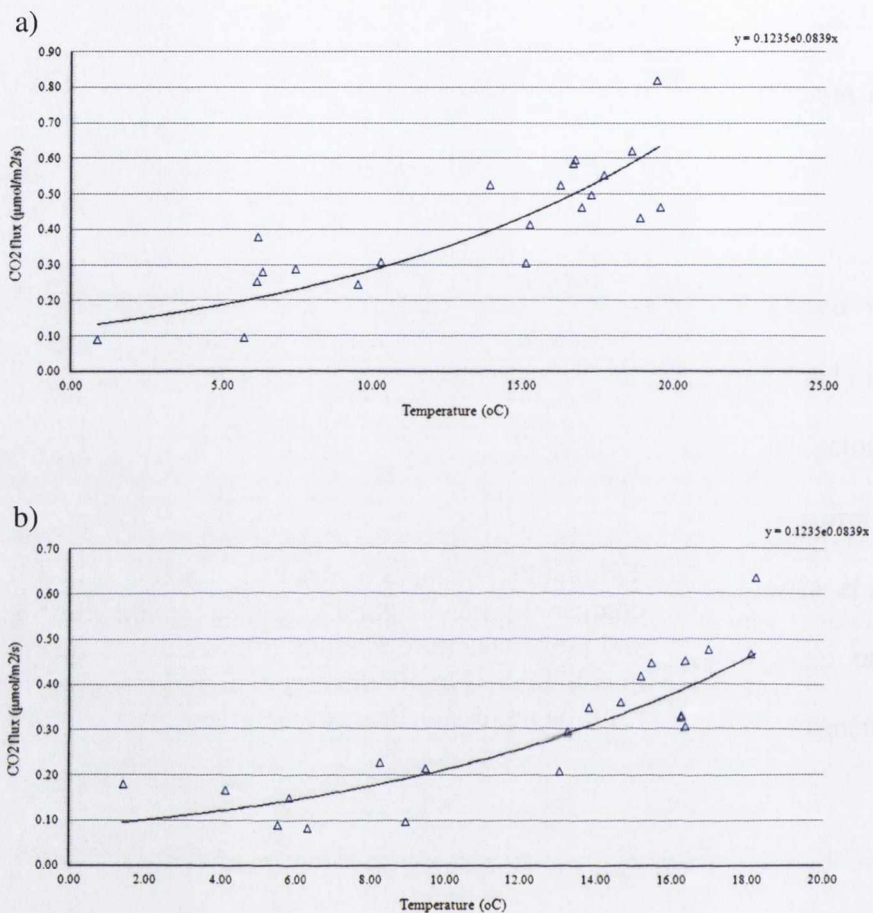


Figure 4.11: Measured soil respiration in the a) treatment and b) control microcosms with temperature. R^2 values were calculated as a) 0.7114 and b) 0.7004 and the exponential function is displayed on graph. Data are replicates of four different canopies.

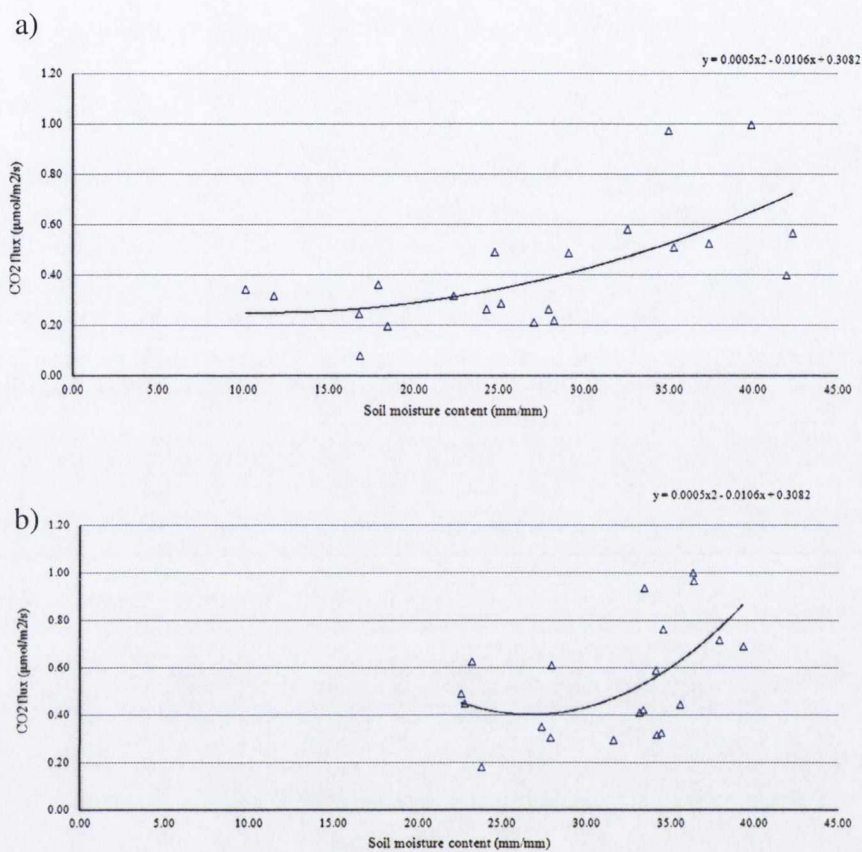


Figure 4.12: Measured soil respiration in the a) treatment and b) control microcosms with soil moisture. R^2 values were calculated as a) 0.42 and b) 0.32 and the quadratic function is displayed on graph. Data are replicates of four different canopy enclosures ($n=4$). $P < 0.05$

4.2.3 Monthly fluxes

The measured CO₂ fluxes presented in the previous sections reflects the net ecosystem exchange (NEE) of the *Lolium perenne* monocultures. The carbon budget of any ecosystem is determined by the amount of carbon fixed by the plants which is in turn the difference between the two main flux components: gross primary production (GPP) and respiration (R). As part of the experimental set up in Oak Park research centre in Carlow we were able to measure daily NEE over the monocultures of *Lolium perenne*. Daytime respiration rates were extrapolated based on the methodology described in section 4.2.2 and therefore we were able to provide an estimate of GPP based on the equation:

$$GPP = R_e - NEE$$

Where R_e is defined as the total ecosystem respiration and is the sum of day and night time respiration rates, and NEE is the measured daytime CO₂ flux rates recorded in each of the four microcosms. These steps were carried out separately for both 2008 and 2009.

The cumulative monthly NEE exchange for the monocultures of *Lolium perenne* in the control and treatment microcosms for 2008 is given in Figures 4.13 and 4.14. The monthly cumulative GPP and R over the same period are given in Figures 4.15 and 4.16 (a, b). For the treatment microcosms, the NEE followed an expected seasonal pattern of CO₂

uptake during the spring and summer months and a release of CO₂ during the autumn and winter months. Peak cumulative monthly uptake of CO₂, was calculated in the treatment microcosms in May at approximately 58 g C m⁻² (Figure 4.13), where GPP and R in the same month were calculated at 100 and 48 g C m⁻² respectively (Figure 4.15,b). Peak GPP was recorded in August (~150 g C m⁻²) and peak R was recorded in December 2008 (~ -210 g C m⁻²), which is also the same month when peak CO₂ is released due to very low rates of GPP. In the control microcosms, however, the pattern of uptake and release was different when compared with the treatment microcosms, as during May, June and July in 2008 there was a net release of CO₂ from the monocultures of *Lolium perenne* (Figure 4.13). Peak monthly CO₂ uptake of CO₂ was calculated in April (40 g C m⁻²), peak monthly cumulative release of CO₂, was recorded in October (130 g C m⁻²). From May until December the rates of CO₂ losses remained relatively high, ranging from approximately -80 g C m⁻² to -180 g C m⁻², with peak values recorded in October. GPP values were lower in each month than compared with treatment microcosms, however a peak cumulative value was recorded in July at ~ 150 g C m⁻² (Figure 4.15,a).

The cumulative monthly NEE exchange for the monocultures of *Lolium perenne* in the control and treatment microcosms for 2009 is given in Figure 4.14. The cumulative GPP and R over the same period are given in Figures 4.16 (a and b). For the initial six months of 2009, the treatment and control monocultures of *Lolium perenne*, followed a

similar pattern of uptake and release in each month, in terms of NEE, GPP and R although the magnitude of these values were different. Where for example peak cumulative NEE was recorded in the April in both the treatment and control microcosms at approximately ~ 115 and 85 g C m^{-2} respectively. Similarly the peak cumulative GPP and R was recorded in both the treatment and control microcosms in May (Figure 4.16, a and b). However over the final three measurement months in the treatment and control microcosms the magnitude and direction of the cumulative NEE was opposite as in the treatment microcosms there was a net uptake of CO_2 and in the control microcosms there was a release of CO_2 .

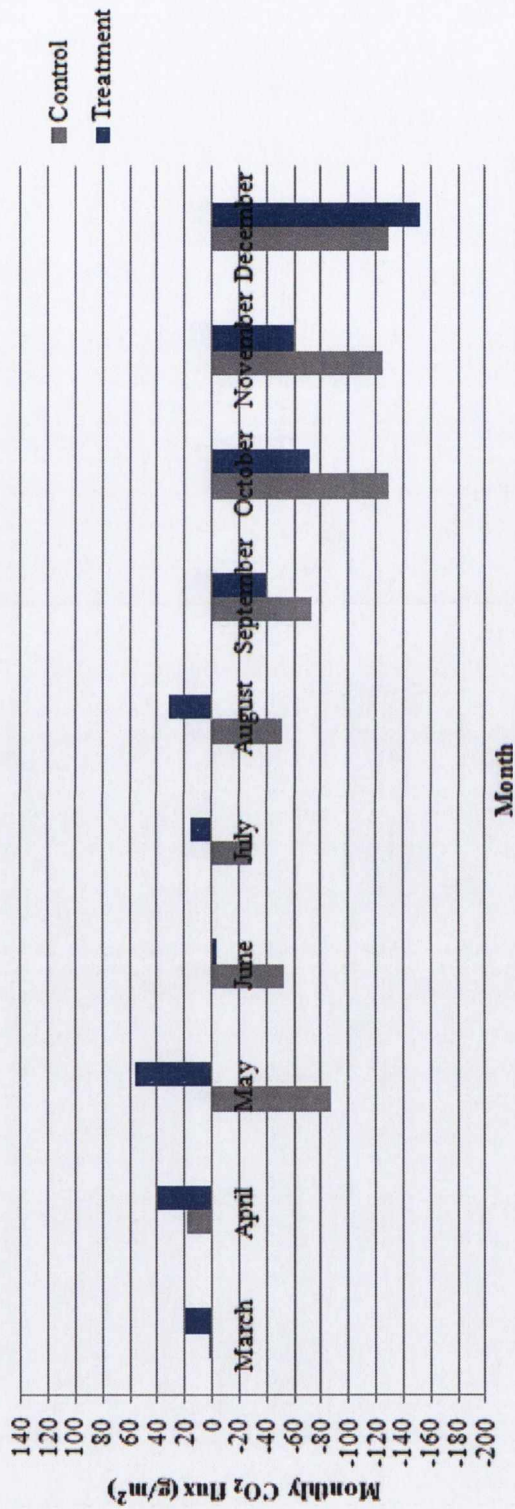


Figure 4.13: Monthly NEE for the treatment (blue) and control (grey) microcosms for 2008. Data represent the average of four replicates (n=4), where there was no statistically significant difference between the measured values ($P < 0.05$)



Figure 4.14: Monthly NEE for the treatment (blue) and control (grey) microcosms for 2009. Data represent the average of four replicates (n=4), where there was no statistically significant difference between the measured values ($P < 0.05$)

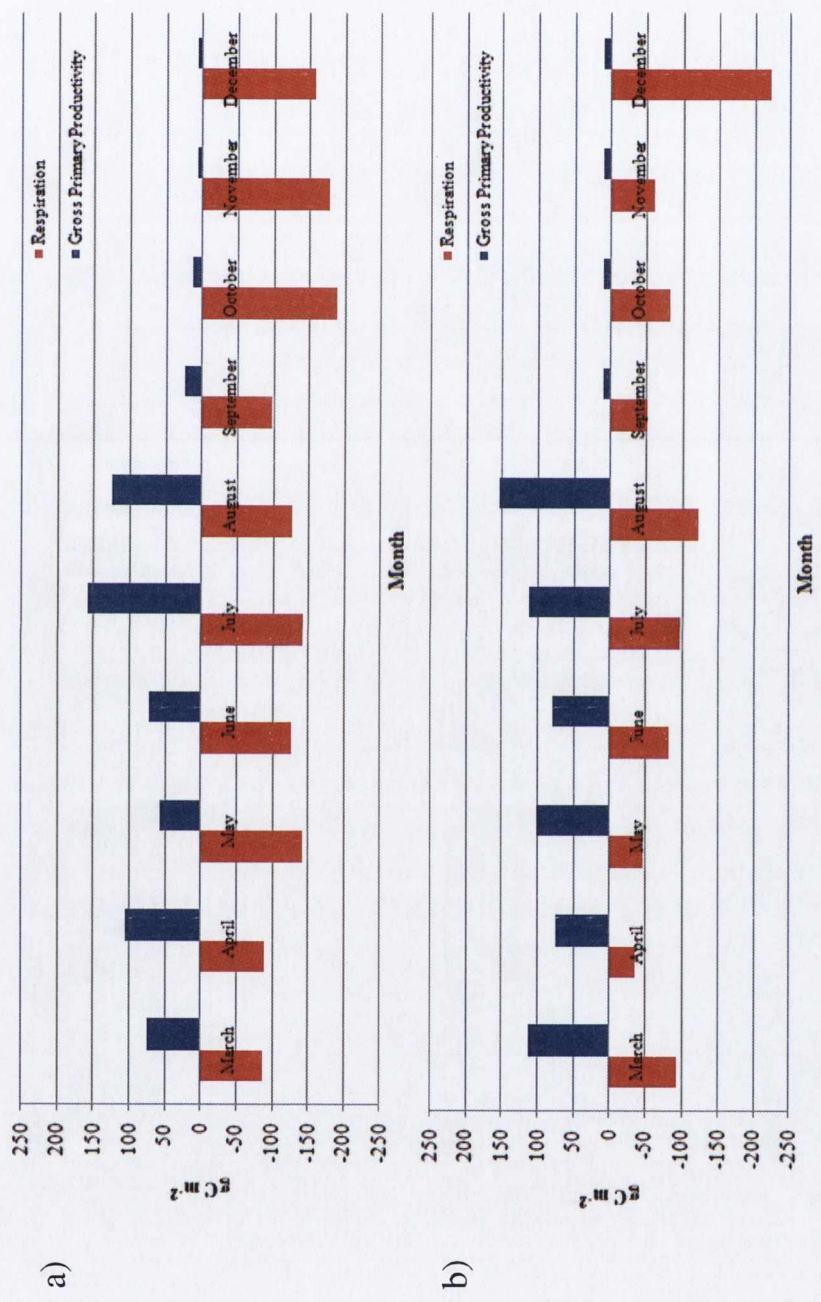


Figure 4.15: Monthly GPP (blue) and R (red) for the control (a) and treatment (b) microcosms in 2008, Data represent the average of four replicates (n=4), where there was no statistically significant difference between the measured values (P < 0.05)

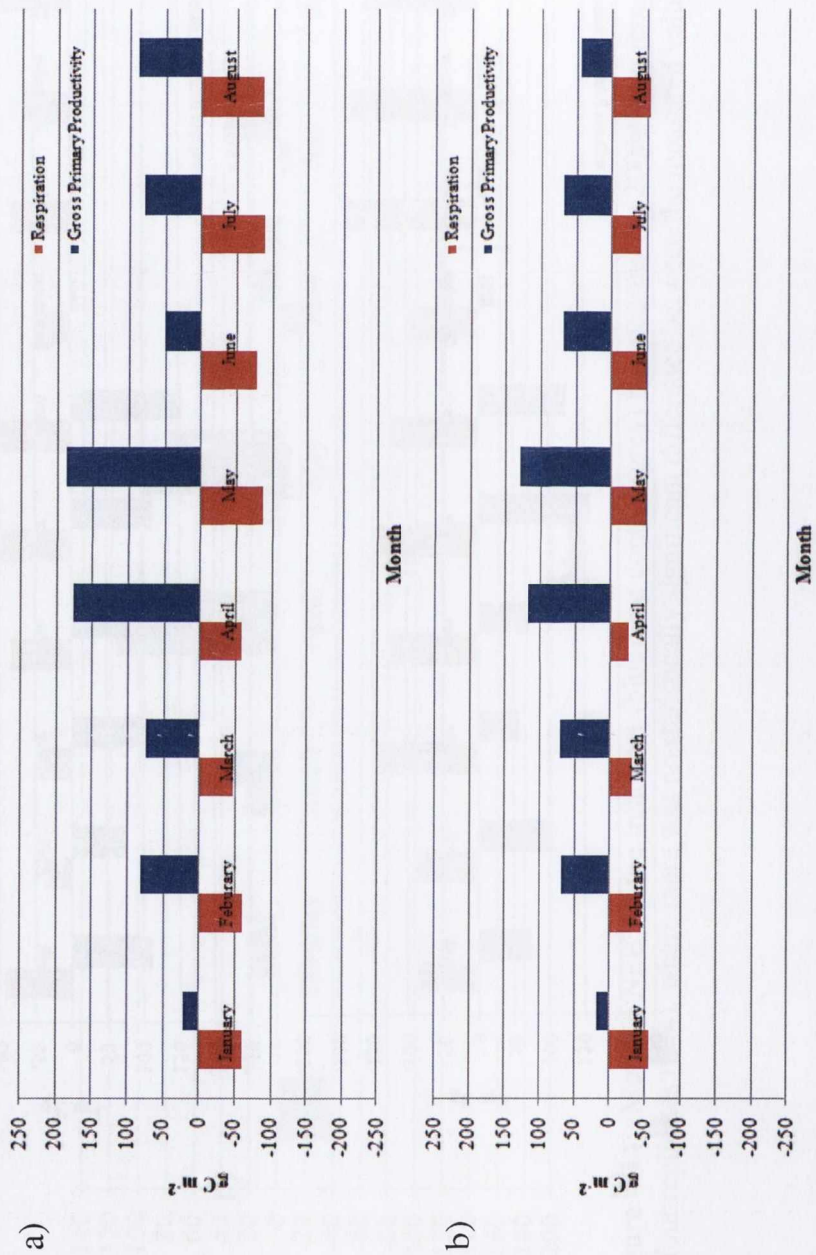


Figure 4.16: Monthly GPP (blue) and R (red) for the control (a) and treatment (b) microcosms in 2009, Data represent the average of four replicates (n=4), where there was no statistically significant difference between the measured values ($P < 0.05$)

4.3 Monthly biomass harvests

As described in section 2.4.4 (chapter 2), as part of the experimental set up we took four monthly harvests of the biomass within each microcosm. The samples were then weighed, dried and re-weighed and the average biomass for the treatment and control microcosms was averaged over the four replicates. The total biomass produced was approximately 1087 g DM m⁻² and 1003 g DM m⁻² in the treatment and control microcosms respectively in 2008 (Figure 4.17), with peak biomass recorded of 262 and 333 g DM m⁻² yielded in July for both the treatment and control microcosms.

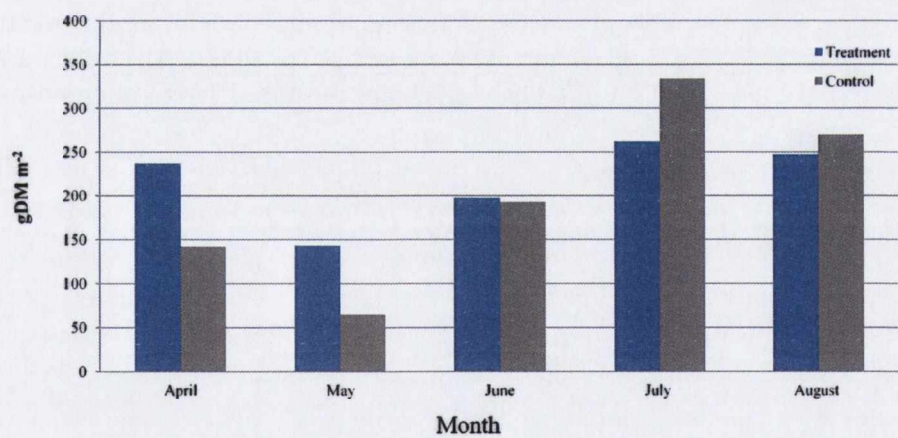


Figure 4.17: Average biomass yield in the treatment (blue) and control microcosms (grey) for 2008. All values are expressed in g DM m². Data are means of four different microcosms (n=4). P < 0.05

For 2009 the total biomass harvest was recorded as 1170 and 1123 g DM m⁻² for the treatment and control microcosms respectively (figure 5.14), with a peak biomass of 363 and 348 g DM m⁻² recorded in May.

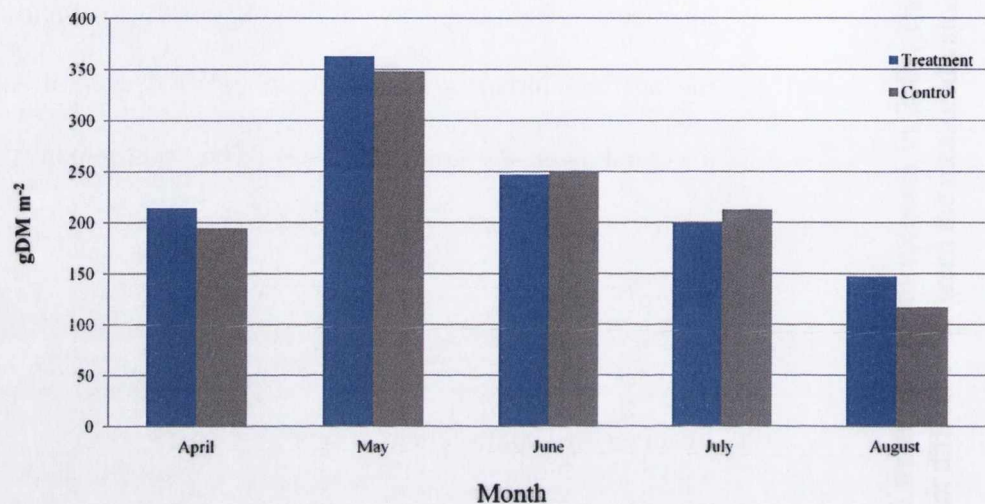


Figure 4.18: Average biomass yield in the treatment (blue) and control microcosms (grey) for 2009. All values are expressed in g DM m². Data are means of four different microcosms (n=4). P < 0.05

4.4 Carbon balance

Estimates of the different components of the annual carbon balance were calculated as given in section 4.2.3. Figures 4.19 to 4.22 shows the cumulative GPP, R and NEE for the treatment and control microcosms from the period March to December in 2008 and January to September in 2009, table 4.3 summarises the cumulative NEE, R and GPP with the standard deviation across all the microcosms values in grams of carbon per m² for the same period in 2008 and 2009, as indicated previously.

	Treatment	Control
2008		
<i>GPP</i>	694.2 +/- 15	632.4 +/- 15
<i>R</i>	-888 +/- 9	-1,170 +/- 20
<i>NEE</i>	-194.6 +/- 25	-538 +/- 50
2009		
<i>GPP</i>	581 +/-11.5	759.7 +/- 16
<i>R</i>	-352 +/- 15	-563.9 +/- 13
<i>NEE</i>	229.4 +/- 16	195.8 +/- 20

Table 4.3: Cumulative NEE (net ecosystem exchange), R (respiration) and GPP (gross primary productivity) for the treatment and control microcosms for 2008 and 2009. All values are expressed in g C m⁻². Data are means of four different microcosms (n=4) and include estimates of the standard deviation

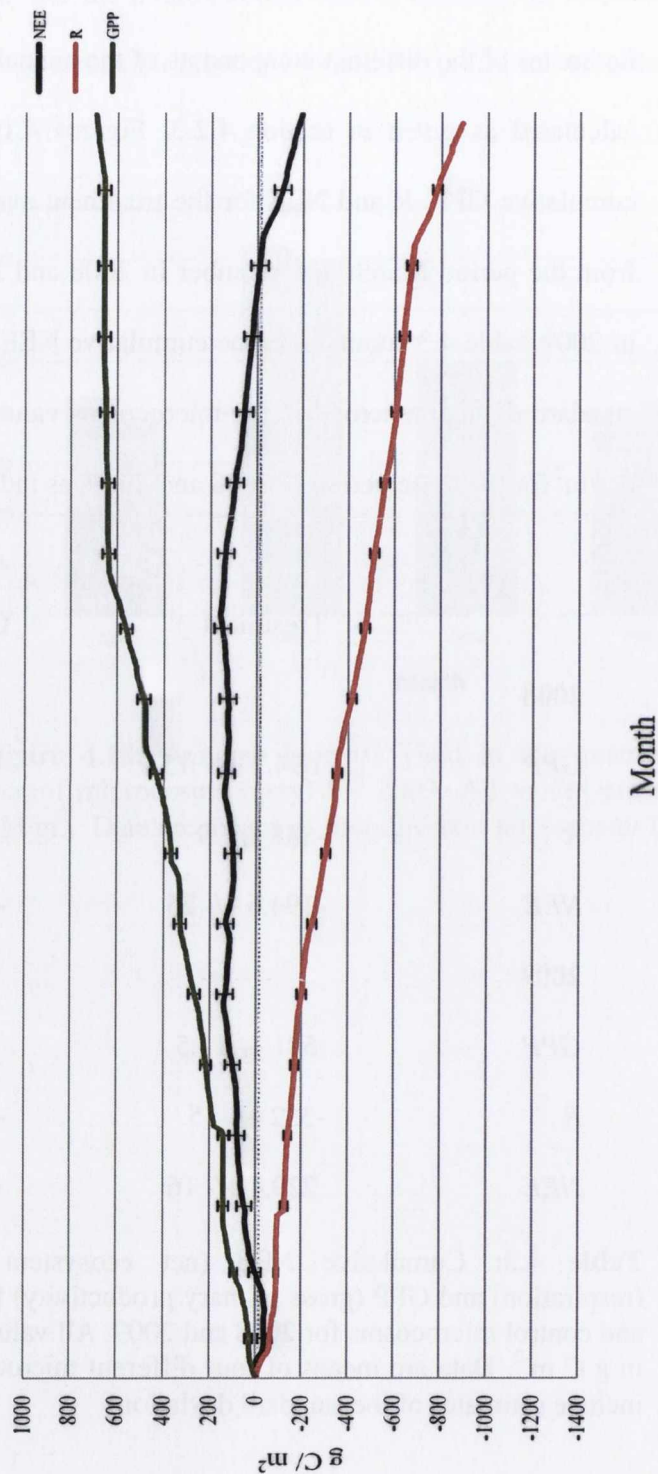


Figure 4.19: Cumulative NEE (black), R (red) and GPP (green) for the treatment microcosms in 2008. All values are expressed in T C/ ha. Data represent the average across four replicates (n=4), error bars represent the standard deviation in recorded temperature at two week intervals

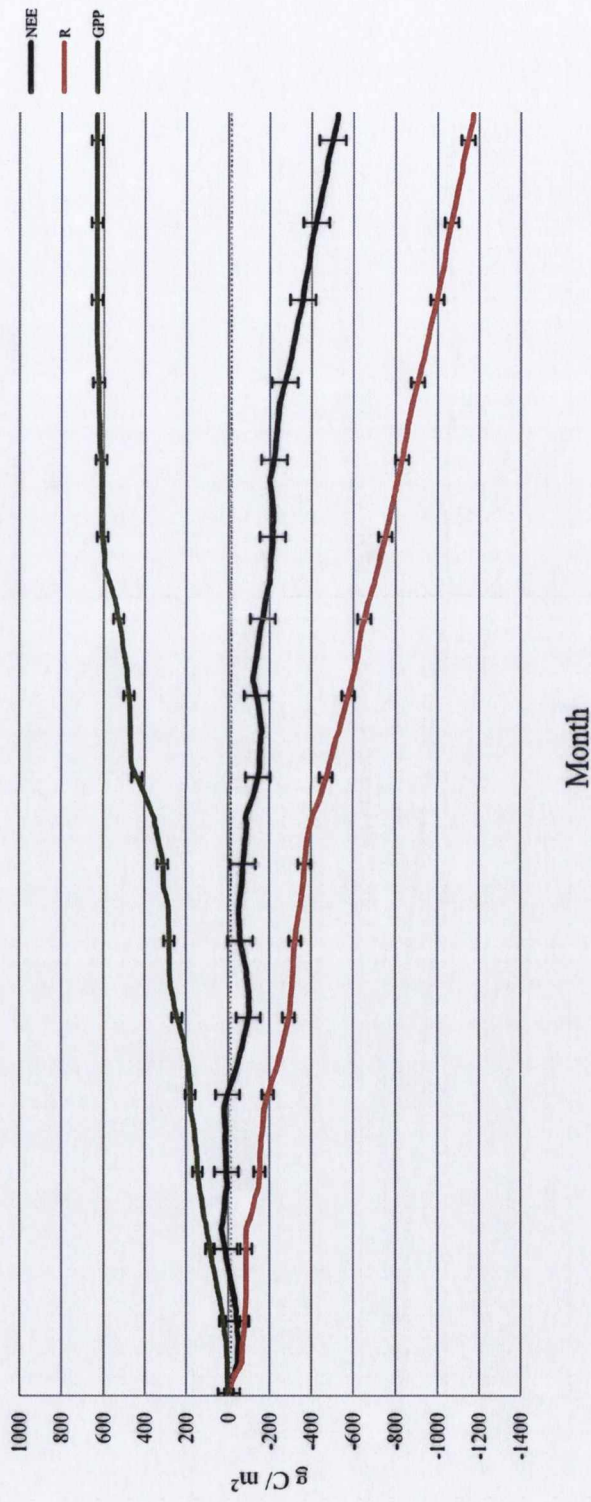


Figure 4.20: Cumulative NEE (black), R (red) and GPP (green) for the control microcosms in 2008. All values are expressed in T C/ ha. Data represent the average across four replicates (n=4), error bars represent the standard deviation in recorded temperature at two week intervals

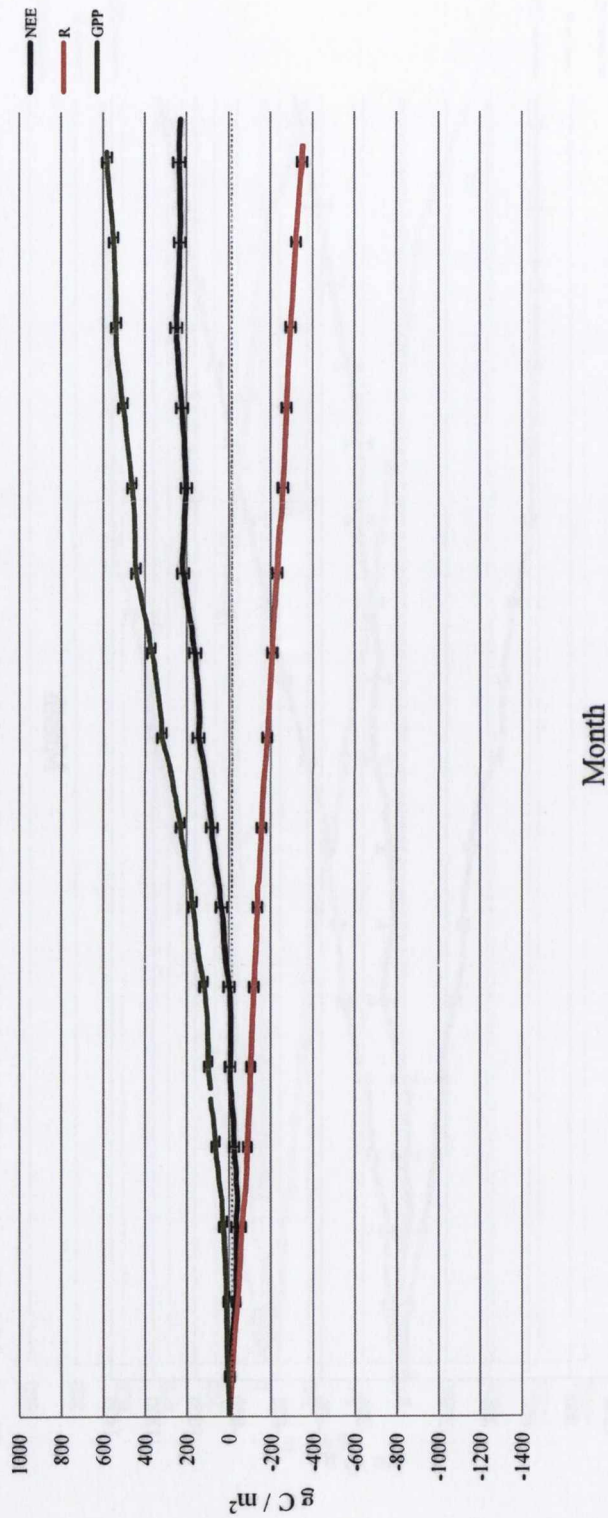


Figure 4.21: Cumulative NEE (black), R (red) and GPP (green) for the treatment microcosms in 2009. All values are expressed in g C/ha . Data represent the average across four replicates ($n=4$), error bars represent the standard deviation in recorded temperature at two week intervals

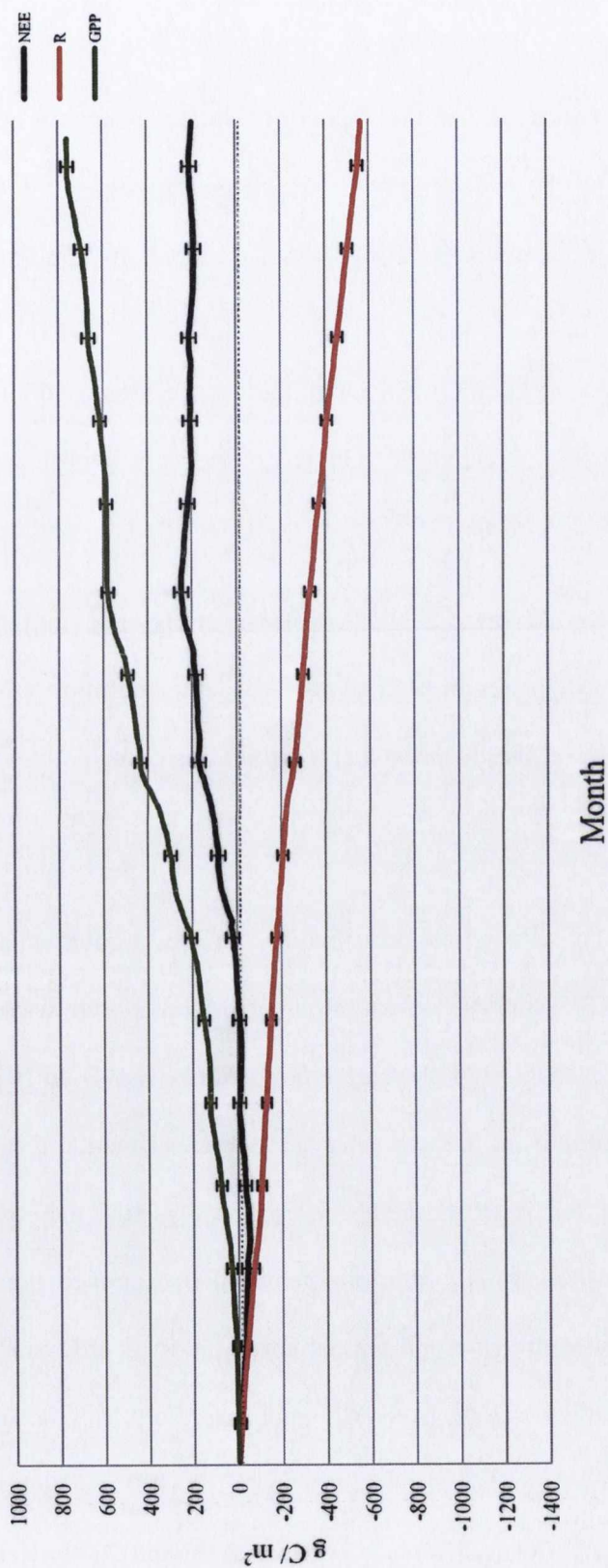


Figure 4.22: Cumulative NEE (black), R (red) and GPP (green) for the control microcosms in 2009. All values are expressed in g C/ha . Data represent the average across four replicates ($n=4$), error bars represent the standard deviation in recorded temperature at two week intervals

4.5 The statistical relationships between the microcosms

To investigate the impact of climate change on net ecosystem exchange (NEE) and its principal components, respiration (R) and gross primary productivity (GPP) we initially adopted two null hypothesis;

- a) The climatic variables temperature and soil moisture and hence NEE, GPP and R do not vary significantly on an interannual basis
- b) There is no significant difference in the productivity of the treatment and control monocultures of *Lolium perenne* in response to their surrounding climate.

To test for any statistically significant interannual variations in NEE, GPP and R we initially performed a two way analysis of variance (ANOVA) on the mean daily values ($n = 4$) on NEE, GPP and R for the months in the two years that the experimental measurements overlapped (March to September), separately for the treatment and control microcosms. Additionally we also examined the relationship between soil moisture and temperature values recorded in both years. Table 4.4 represents the ANOVA analysis results for the treatment microcosms. The results indicate that for NEE, GPP and R there was a statistically significant difference between 2008 and 2009 measurement period. As a consequence we can reject the null hypothesis (a). Additionally we

found that there was no significant difference in temperature levels and patterns between the years, however there was in terms of soil moisture. For the control microcosms we found that there was a statistically significant variation in the mean daily measured values of NEE and R (table 4.5), however we found that GPP between both years remained relatively similar. However in terms of the climatic variables measured within the control microcosms we found that there was a statistically significant difference in measured soil moisture content (table 4.5), whereas temperature remained relatively similar.

To help explain the differences between measured NEE, GPP and R in both the treatment and control microcosms and also to address hypothesis (b) we also performed a correlation analysis on each of the 'dependent' variables NEE, GPP and R to observe how each value was affected by temperature and precipitation for the control measurements (table 4.6 and 4.7) and also the treatment measurements (table 4.8 and 4.9). Where positive values indicate a positive correlation between the principal components and negative values indicate a negative correlation between the principal components.

Net ecosystem exchange (NEE)	0.7453**
Respiration (R)	0.591**
Gross primary productivity (GPP)	0.653**
Temperature	0.0001*
Soil moisture content	0.7861**
* Indicates that we cannot reject null hypothesis (a)	
** Indicates that we can reject null hypothesis (a)	

Table 4.4: Represents the analysis of variance (ANOVA) between NEE, GPP, R, temperature and soil moisture content for 2008 and 2009 measured in the treatment microcosms. The statistical test was only performed on data recorded in March to September in 2008 and 2009

Net ecosystem exchange (NEE)	0.6924 ^{**}
Respiration (R)	0.732 ^{**}
Gross primary productivity (GPP)	0 [*]
Temperature	0.0001 [*]
Soil moisture content	0.5844 [*]
* Indicates that we cannot reject null hypothesis (a)	
** Indicates that we can reject null hypothesis (a)	

Table4.5: Represents the analysis of variance (ANOVA) between NEE, GPP, R, temperature and soil moisture content for 2008 and 2009 measured in the control microcosms. The statistical test was only performed on data recorded in March to September in 2008 and 2009

	Respiration (R)		Gross primary productivity (GPP)	
	2008	2009	2008	2009
Temperature	0.522	0.412	0.253	0.04
Soil moisture	0.002	0.089	0.317	0.449

Table 4.6: Represents the regression analysis between respiration (R) and Gross primary productivity (GPP) and soil moisture and temperature measured within the treatment microcosms. Values given represent the r^2 values. The statistical test was only performed on data recorded in March to September in 2008 and 2009

	Respiration (R)		Gross primary productivity (GPP)	
	2008	2009	2008	2009
Temperature	0.723	0.681	0.288	0.11
Soil moisture	0.138	0.061	0.442	0.31

Table 4.7: Represents the regression analysis between respiration (R) and Gross primary productivity (GPP) and soil moisture and temperature measured within the control microcosms. Values given represent the r^2 values. The statistical test was only performed on data recorded in March to September in 2008 and 2009

Chapter 5:

5: Discussion: The impact of ambient and climate change on interannual NEE, GPP and R

5.1 Interannual variation in NEE

Historically, intensive agricultural land management has caused soil C losses in agricultural systems (Smith *et al.*, 2004a), and this is most apparent for cropping systems. Grasslands are by their nature less intensively managed than croplands and therefore tend to retain more C (Jones *et al.*, 2004). However, most grassland ecosystems exhibit a large interannual variability in their annual NEE (Flanagan *et al.*, 2002, Ma *et al.*, 2007) and as a consequence their role in the global C cycle remains uncertain. C flux dynamics in grasslands tends to vary depending on the climatic conditions and also management practices (Knapp *et al.*, 2002; Verburg *et al.*, 2004; Derner *et al.*, 2006.)

The cumulative annual NEE, GPP and R exchange for the monocultures of *L. perenne* in the treatment and control microcosms for 2008 and 2009 are given in Figures 4.19 to 4.22 and yearly totals are presented in table 4.3. In 2008 both the treatment and control swards of *L. perenne* were a source of CO₂ at -194.6 (+/- 25) and -538 (+/- 50) g C m⁻² respectively. For 2009 both acted as a sink of CO₂ at 229.4 (+/- 16) and 195.8 (+/- 20) g C m⁻² for the treatment and control microcosms. These values are significantly lower than those presented by Klumpp *et al.*, (2007) who reported values in the range of 1200 – 1700 g C m⁻² year⁻¹, but well within the range presented in mesocosm experiments (Casella

and Sousanna, 1997) and eddy covariance flux measurements (Xu & Baldocchi, 2004; Novick *et al.*, 2004).

To explain the differences in NEE in the treatment and control microcosms between 2008 and 2009 we examined the pattern of the environmental drivers of NEE and its components, GPP and R, between both years. As described in Chapter 4, table 4.4 and 4.5, the temperature pattern between 2008 and 2009 did not statistically differ however; we found there was a statistically significant difference in soil moisture contents between 2008 and 2009.

As discussed in chapter 1, grassland productivity is limited by seasonal water variability (Knapp and Smith, 2001; Weltzin *et al.*, 2003; Hao *et al.*, 2010) and the alteration in rainfall patterns will affect the productivity of grasslands. Recent studies have shown that the annual amount and timing of precipitation remains the dominant factor in regulating NEE exchange in grasslands (Suyker *et al.*, 2003; Hunt *et al.*, 2004; Xu and Baldocchi, 2004), temperate grasslands exhibit asymmetric responses to interannual variations in precipitation (Fu *et al.*, 2009). Or more specifically during wet years the increase in productivity is more pronounced than the reductions in dry years (Wever *et al.*, 2002; Flanagan *et al.*, 2002, Fu *et al.*, 2009).

For example in 2008 we measured a decline in the soil moisture contents of the control microcosms, and hence treatment, which in turn lead to a decline in GPP. In March 2008, there was a relatively sharp decline in the soil moisture status followed by a subsequent rise in April which then declined again in May. This was then repeated in July and August,

i.e. the peak summer months, whereby the soil moisture status again declined from early August until September. This pattern was also repeated in 2009, however with regards to the decline in soil moisture during March, April and May was more gradual, i.e. the soil moisture status in early spring 2009 was higher than in 2008. This is then subsequently reflected in the monthly NEE values (Figures 4.13 and 4.14, chapter 4) and the components of NEE (Figure 4.15 and 4.16, chapter 4). Values recorded in the control microcosms show that for March and April in 2008 and 2009 the *L. perenne* monocultures initially acted as a sink of CO₂ however in 2008 they rapidly shifted to a source of CO₂ and remained so for the remainder of the year. This pattern was not repeated in 2009, as the *L. perenne* monocultures acted only as a source of CO₂ in June and July, which corresponds with the only period that year, when there was a rapid decline in the soil moisture status.

While temperature typically exerts the greatest control on soil respiration rates (Xu and Baldocchi, 2004; Suyster and Vermeer, 2001; Gilmanov *et al.*, 2001), soil moisture contents can influence the rate of soil respiration through the availability of water for use by the plant and also its impact on substrate availability (Flanagan *et al.*, 2005). For both the treatment and control microcosms the measured ecosystem respiration rates were lower in 2009 than in 2008, this difference being most pronounced in the control microcosms (Figure 4.15 and 4.16).

Disturbance events can also have a significant impact on the C cycling within many different ecosystems. In terms of intensively managed Irish grasslands the intensity and timing of grazing or biomass removal for silage, can influence the growth and carbon allocation and therefore affect the amount of carbon accrual in soils (Contant *et al.*, 2001; Freibauer *et al.*, 2004; Contant and Paustian, 2002; Reeder *et al.*, 2004). Quantification of these effects however is still inconsistent due to the range of different grazing/ herbage removal practices employed and the diversity of plant species, soils and climates involved (Schuman *et al.*, 2001; Derner *et al.*, 2006). For the purpose of this experimental set up we kept a similar date for management events, such as biomass removal in 2008 and 2009 so that the C fluxes in both years could be compared (Figures 4.9 and 4.10 (a and b)). In both 2008 and 2009, after the harvest events, as expected there is a sharp decline in NEE in both the treatment and control microcosms, and their respective ability to recover of the monocultures to recover in 2008 and 2009 is dependent on the climatic conditions.

More specifically the average monthly temperature in the treatment microcosms for June and July in 2008 was recorded at 17.5 and 20.8°C, with the soil moisture content recorded as 0.30 m³ m⁻³ and 0.17m³ m⁻³ respectively. Whereas in the control microcosms the average monthly temperatures were 16.6°C in June and 18.5°C in July and the average soil moisture content was recorded at 0.24 m³ m⁻³ and 0.30 m³ m⁻³ for the same period, leading to a wetter soil status which will respire more. This means that despite lower GPP values, the treatment microcosms remain

a sink of CO₂ due to lower soil respiration rates; however in the control microcosms the higher R rates after the biomass harvests mean that they become sources of CO₂ during these months. In a study on the impact of the frequency of disturbance events on the productivity of grasslands Klumpp *et al.*, (2007) found that frequent disturbance events can stimulate grassland productivity and lead to an increased uptake of CO₂. The more favourable climatic conditions in 2009, as compared with 2008, reflected these findings as in general the *L. perenne* monocultures remained as a sink of CO₂ with high biomass production values (Figures 4.17 and 4.18, chapter 4) however in 2008 the biomass production in the same period was suppressed due to the significantly lower soil moisture values throughout April and May.

5.2 Variations in Net Ecosystem Exchange due to climate change

For 2008 we found that the control microcosms initially acted a sink of CO₂ and then switched rapidly to a source of CO₂, with the biggest losses recorded in May at approximately -90 g m⁻² (Figure 4.13., chapter 4), and remained so for the remainder of the year. During this period and when compared with previous months, we observed a sharp decline in GPP and a sharp rise in soil respiration rates (Figure 4.15 a). However during 2008, we observed a different pattern in NEE within the treatment microcosms. For 2008 the treatment microcosms primarily acted as a sink of CO₂ from March until September with the average cumulative monthly NEE ranging from +20 g m⁻² to +60 g m⁻².

When we consider 2009 the differences in the NEE for the treatment and control microcosms from February to June both the treatment and control microcosms acted as sinks of CO₂. The average cumulative NEE varied for each month but in general the control microcosms acted as a greater sink of CO₂ (max. recorded value $\sim +120 \text{ g m}^{-2}$) than the treatment microcosms (max. recorded value $\sim +85 \text{ g m}^{-2}$). This however changes from June onwards when the control microcosms then acted as a small source of CO₂ with the treatment microcosms acting as a small sink.

Based on the statistical analysis provided in chapter 4 (tables 4.6 and 4.7), temperature was found have the greatest impact on the respiration rates whereas soil moisture contents were found to have the greatest impact on GPP, this is also broadly in line with other wide ranging experiments (Gilmanov *et al.*, 2006). Under the climate predictions provided by Sweeney *et al.*, (2003), in general there was an increase over the winter, autumn and early spring months however there is an expected sharp decline in precipitation levels during the summer months, where for example in July there is an expected 55% decrease.

Net ecosystem exchange in the control microcosms switched rapidly from a sink of CO₂ in April to a source of CO₂ in May 2008 and then subsequent months whereas the treatment microcosms remained a sink of CO₂ for the same period. This was coupled with a sharp decline in the soil moisture status within the control microcosms (figure 3.12, chapter 3), which lead to a sharp decline in GPP (Figure 4.15(a)). During these months however the modelled difference in precipitation for these

months was a 12% increase in precipitation (table 2.1), with the result that the soil moisture status remained higher in the treatment microcosms during the spring months. However during the remainder of the year, despite an increase in soil moisture contents in the control microcosms, and a corresponding decline in the treatment microcosms soil moisture status especially in July and August (Figure 3.12, chapter 3) there was still a net gain in C in the treatment microcosms and not the control microcosms.

In 2009 the differences between the control and treatment microcosms were less pronounced as the pattern of the soil moisture status remains relatively constant throughout the year, except for in June and July in the treatment microcosms, where we imposed a decline in the soil moisture status (as in table 2.1). Therefore over the course of the experimental period we found that when the soil moisture status declined there was a subsequent decline in GPP, and vice versa, while R, remained relatively insensitive to changes in soil moisture status even under a mild dry period and did not change dramatically in relation to the soil moisture status (table 4.6 and 4.7, chapter 4). The rapid decline in GPP for 2008 in the control microcosms lead to the *L. perenne* monocultures becoming a source of CO₂ and can be attributed to the drought period in March/April. However, based on the predicted 2050 climate, the moisture status within the treatment microcosms was higher and therefore the swards of *L. perenne* remains as a sink of CO₂.

This was also found in an experiment to determine the impact of precipitation timing and quantity, by Hao *et al.*, (2009), who found that

the duration of CO₂ fluxes and their rate was altered in a dry season, with a longer dry period leading to a significant loss of C. Additionally under reduced rainfall amounts and in a relatively short period of time the grasslands switched from a carbon sink to a source under reduced rainfall amounts (Hao *et al.*, 2009). This was reflected in our experimental measurements especially during the early spring summer period in 2008, as described above. Moreover Kwon *et al.*, (2007) also found that precipitation patterns, which exert a strong control on photosynthetic uptake of CO₂, in spring, can regulate net ecosystem exchange into the summer months as soil moisture availability is limited throughout the growing season due to the growth demands of plants in already dry soils. Therefore the stronger performance of the *L. perenne* in the treatment microcosms even in the drier late summer months may not be unexpected as the considerably wetter spring meant that there was a sufficient deep soil moisture status in the microcosms to maintain plant growth. This also explains the uptake of CO₂ by both the treatment and control microcosms in 2009.

The monthly percentage difference in temperature is presented in Table 2.1 (chapter 2) and in general differences between the treatment and control translated to a 2°C temperature difference. Over the course of the experimental period we found that soil respiration rates were most dependent on temperature (Figures 4.15 and 4.16, chapter 4), however for the treatment microcosms we found a decreased sensitivity in the response of R to temperature, which was reflected in our Q₁₀ values. A possible explanation for this decreased sensitivity is due to acclimation.

Luo *et al.*, (2001 (a)), conducted an experimental warming in natural grasslands and found that the sensitivity of soil respiration to warming decreases after the ecosystem is exposed to experimental warming for shorter periods. Thus short term data may not capture long term characteristics if respiration responses to rising temperatures and may lead to underestimations of soil respiration rates into the future.

Despite this our study showed that during the spring and summer months for both 2008 and 2009 there were lower rates of R in the treatment microcosms, as compared to the control. Therefore while temperature levels may have increased, substrate and water availability and the decreased sensitivity of R limited the rate of CO₂ being emitted from the treatment swards of *L. perenne*. During the winter months, there was a change in the dynamics of R which was especially pronounced in December where we observed a rapid increase in the rate of R which may be a consequence of increased decomposition rates due to differences in the degradation of organic C in compounds (Davidson & Janssens, 2006; Paz-Ferreiro: 2011). The significant losses of CO₂ observed from our swards of *L. perenne* can occur from temperate pastures during the winter months, and in some cases can turn grasslands from sinks of CO₂ to sources (McGinn & King, 1990; Skinner *et al.*, 2007). This is in part due to a change in the balance of NEE, as CO₂ uptake decreases as light levels diminish and defoliation takes place (McGinn and King, 1990), soil respiration rates remain constant, and can do so even when soil temperatures are below 0°C (Frank *et al.*, 2002). Therefore changes in soil respiration rates also have important

implications for the C budgets of grasslands. Over the course of 2008, the treatment microcosms remained as a sink of CO₂, however during the winter months became a significant source of CO₂, which was smaller in magnitude when compared with the control microcosms.

Chapter 6:

6: Final discussion and conclusions from the microcosm experimental study

This study aimed to quantify the impacts of two environmental variables, temperature and precipitation, on the magnitude and direction of NEE on *L. perenne* swards under the same management. This to our knowledge represents the first continuous field based study to investigate the potential impact of climate change on managed grasslands in Ireland.

To achieve this we proposed (a) the use of multiple microcosms to replicate both the ambient and future climate (2050) and expose swards of *L. perenne* to the two climate treatments. From this we aimed to (b) examine the difference in NEE and assess the potential impact of environmental drivers on that its components, GPP and R, and also to investigate (c) the potential impact climate change will have on the productivity of Irish grasslands. Finally we aim to (d) define future research needs and questions that may need to be addressed by policy makers. Each of these will be discussed in more detail in the following sections.

6.1 Advantages and performance of the multiple microcosm enclosure facilities

Chapter 3 describes the microcosm system in detail, however in general this system allowed for:

- (i) Continuous measurements of carbon fluxes, in a non destructive manner

(ii) Realistic replication of the ambient climate and its manipulation where required

(iii) Continuous monitoring of 4 replicates of each climate scenario.

Despite this, the microcosm enclosures still have some practical limitations that may have an effect on the overall results (Keller *et al.*, 2004; Verburg *et al.*, 2004; Klumpp *et al.*, 2007). More specifically, light transmission through the sides of enclosures was increased, when compared with dense swards in normal field conditions. The increased light levels throughout the swards may lead to a slightly higher rate of CO₂ fluxes (Klumpp *et al.*, 2007). Additionally, as described in chapter 3, in order for CO₂ fluxes to be measured within the microcosms air was continuously circulated within each chamber. The decrease in aerodynamic resistance created by this air flow may increase the rate of photosynthesis when compared with plants that are grown under non-ventilated conditions, as in an external environment there may not be continual flow of air over a canopy (Kanechi *et al.*, 1998; Bergez and Dupraz, 2000; Klumpp *et al.*, 2007). In addition departures from the average annual climate can also impact on the experimental protocol. For example Klumpp *et al.*, 2007, which also measured NEE in grasslands, experienced an unexpected heat-wave during their experimental period. As a consequence they had to lower the temperatures and manually water the swards to prevent sward damage, which altered the annual NEE and led to higher values recorded than may be expected. However, as detailed in chapter 3, in 2008 and 2009

the climate was not subjected to departures from long term average temperature. More specifically the average annual temperatures recorded in the control microcosms was, 14.1 °C and 12.7 °C for 2008 and 2009 respectively. Therefore we were not required to adjust the temperature and precipitation levels within the microcosms.

Chapter 4 outlines the performance of the microcosm enclosures in simulating the differences between the temperature and precipitation based on the climatic projections for temperature and precipitation produced by Sweeney *et al.*, 2003 (table 2.1). Sweeney (2003) estimated an 18.8% increase in temperature relative to the ambient baseline. For this experiment we were able to replicate an average annual increase of 19.03% in 2008 and 16.67% increase in temperature in 2009. Based on the average air temperature recorded within the control microcosm, the average annual increase in temperature of 18.75% would correspond to a 2.66°C increase, for this experiment we were therefore able to simulate a 2.78°C increase in 2008 and a 2.3°C increase in 2009.

Differences in the soil moisture status between the treatment and control microcosms can either be positive or negative depending on the time of year, and are presented in Figure 3.14 (chapter 3). On an annual basis, Sweeney (2003) predicted through modelling an 11% decrease in precipitation. For this experiment in 2008 we achieved a 9.0% and 8.7% decrease in precipitation compared to the ambient baseline for 2008 and 2009 respectively. Overall we found good agreement between the percentage differences achieved within the treatment microcosms and than those projected by Sweeney *et al.*, (2003).

6.2 Assessing the impact of climate drivers and climate change on Net Ecosystem Exchange

The second aim of this study was to measure NEE fluxes over monocultures of *L. perenne* and assesses the impact of the environmental drivers, temperature and precipitation, on its magnitude and direction. Thirdly we aimed to investigate the impact future climate change will have on the productivity of grasslands, when compared directly with ambient NEE.

Although the short term data obtained in this study offers us a limited predictability of ecosystem response to climate change our experimental work demonstrates that both the rate of ecosystem respiration and photosynthesis are driven by different climate factors, whose impact varies depending the annual patterns of the climatic variables. Overall our study showed that between both years NEE for the *L. perenne* swards showed considerable interannual variability switching from a source to a sink of CO₂. This was primarily driven by changes in precipitation patterns and levels, during the growing season. However, over the two years we found for both years, the *L. perenne* swards grown within the treatment microcosms performed better than those grown in the control microcosms, i.e. there was less C lost to the atmosphere when compared with the control in 2008 and greater uptake of C in 2009 (table 4.3). More specifically our results showed:

- a) On an annual basis the timing and quantity of rainfall events, exerted the strongest influence on GPP for both the treatment and control microcosms. The higher rainfall amounts in 2009, especially during the growing season, translated into an increase in GPP, as compared with the same period in 2008. In addition to this, the decline in precipitation levels during the summer months, which was more pronounced in the treatment microcosms than the control, translated into a decline in the rate of C uptake as water and substrate availability became more limited.
- b) Similarly temperature exerted the strongest influence on the interannual variability of R. Over the course of the experimental period annual temperature patterns between 2008 and 2009 were similar as were yearly averages (chapter 3). However while we observed typical seasonal patterns in the rates of R, soil moisture contents which also acts as a constraint on substrate availability influenced the rates of R between the years.
- c) The impact of management practices, such as biomass harvests, have a large impact on the NEE of the monocultures of *L. perenne*.
- d) In terms of climate change, the role of the environmental drivers may have a significant impact on the annual NEE budget, due to

its influence on the seasonality of grassland productivity. More specifically during the early spring/ summer months, precipitation levels in 2055 are expected to increase, as compared to ambient levels as precipitation levels, especially at the beginning of the growing season plays an important role in subsequent annual plant growth, as drier conditions can restrict early leaf development. Predicted changes in precipitation, for 2055 expect an increase in levels from January to and including April, and from our experimental work, resulted in a higher uptake in C by the swards of *L. perenne* within the treatment microcosms. Although the predicted drier conditions, in the summer of 2055, lead to a decline in GPP in the treatment microcosms, as plant growth was inhibited due to water availability, which was especially apparent in July, August and September, when compared to the control microcosms the productivity of the grasslands was not severely inhibited as reflected in biomass yields.

However, we found that the responses of R to climate change may have the most significant impact on the annual C balance of Irish grasslands. Although it may be expected that higher temperatures may lead to higher soil respiration rates, we measured, for both years, a lower rate of R in the treatment microcosms than compared with the control. This was primarily due to the decreased sensitivity of soil respiration to temperature as reflected in the calculated Q_{10} values and limitations due to

soil water and substrate availability. As a consequence in both years the treatment swards acted either as a sink of CO₂ or, in the case of slightly drier years (2008), as a smaller source of CO₂ when compared to current grassland NEE status.

6.3 Conclusions and Future Work

Our results indicate that temperature and precipitation changes to 2050 may not be detrimental to the productivity of Irish grasslands. This may not be entirely unexpected the Irish climate is currently classified as cool moist and rarely is subject to extremes in climate. Where there may be some concern is during the summer months in which severe droughts as lower precipitation levels with higher temperatures will limit water availability. However slight changes in management practices such as changes in biomass harvest timing coupled with investment in water collection facilities which allows for irrigation, Irish grasslands offer the potential of being sinks of CO₂ as well as maintaining their productivity. This potential however requires more experimental based work coupled with modelling analysis to understand the direction of productivity of *L. perenne*. Additionally this work only is concerned with the changing climate up until 2050, and while *L. perenne*, may still be a feasible crop until then, future trends in climate change beyond has to be considered.

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