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**The Carbon Cycle of an Energy Crop:
Miscanthus x giganteus.**

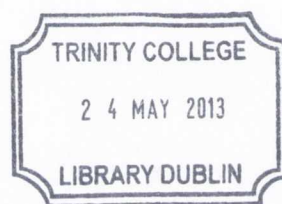
By

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Thesis submitted for degree of Ph.D.

To the University of Dublin, Trinity College

2012



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Summary:

The United Nations Framework Convention on Climate Change Kyoto Protocol (1997) has driven research towards a reduction of carbon dioxide (CO₂) emissions and the development of alternative energy sources. Energy crops provide the best opportunity to combine a reduction in CO₂ emissions with an increase in renewable electricity generation. The conversion of surplus agricultural land to energy crops has been identified as providing the greatest potential for carbon mitigation across Europe. In Ireland *Miscanthus x giganteus*, a perennial rhizomatous grass from Eastern Asia, has received considerable interest as a suitable energy crop. Field trials have displayed promising yields, up to 26 t DM ha⁻¹ yr⁻¹, with the potential to substitute up to 37% of Ireland's gross electricity generation. However, little research has been directed towards plant-based observations and the potential of *Miscanthus* to mitigate carbon and reduce the greenhouse gas effect. Knowledge of the carbon cycles of bioenergy crops is critical for developing future energy policies. Fluxes of CO₂ from a mature *Miscanthus* stand, located in Oak Park Research Centre, Co. Carlow, were measured using eddy covariance techniques and leaf and soil chambers from August 2006 to 2008.

Net ecosystem exchange fluxes of CO₂ indicate that the *Miscanthus* stand acted as a net carbon sink absorbing 2.7 and 3.9 t C ha⁻¹ yr⁻¹ over the two years under examination. Ecosystem respiration fluxes appeared to be the dominant control on interannual variation. The *Miscanthus* stand was a net carbon sink from April to October and a net carbon source from November to March, this correlated closely to the phenology of the crop. The annual mean soil respiration rate for the *Miscanthus* stand was calculated as 6.59 g CO₂ m⁻² day⁻¹, with maximum rates (10.55 g CO₂ m⁻² day⁻¹) recorded in the summer months and minimum rates (0.52 g CO₂ m⁻² day⁻¹) in the winter. Fluxes from the soil in the *Miscanthus* stand represented 60.25% of the total ecosystem respiration. Typical midday CO₂ assimilation rates from *Miscanthus* leaves were 4 to 6 μmol CO₂ m⁻² s⁻¹ (June to October). Maximum above ground biomass ranged between 23.60 t DM ha⁻¹ and 20.95 t DM ha⁻¹. 96.62% of the below ground biomass was located in the top 30 cm of soil; an average of 6.11 t DM ha⁻¹ of rhizome material and 7.36 t DM ha⁻¹ of root material was recorded at the study site. Litter fall averaged 4.65 and 3.08 t DM ha⁻¹ in both years. A decay constant of 0.58 was derived, indicating that 70% of the litter would decompose over 20 months providing a large amount of organic matter into the ecosystem. Net biomass productivity analysis indicated that the *Miscanthus* ecosystem changed from a near carbon neutral resource (0.47 t C ha⁻¹) in the first study year to a better than carbon neutral energy source in the second study year (0.73 t C ha⁻¹).

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Glossary of Abbreviations used in this document:

ABL	- Atmospheric Boundary Layer
AEZ	- Agro-Ecological Zones
AGB	- Above Ground Biomass
AIR	- Agro-Industrial Research, European Commission
Amax	- Maximum CO ₂ Assimilation Rate
BES	- British Ecological Society
CAP	- Common Agricultural Policy
CarboEurope-IP	- Assessment of the European Terrestrial Carbon Balance - Integrated Project
CHP	- Combined Heat and Power Investment Programme, Ireland
DAFF	- Department of Agriculture, Fisheries and Food
DEFRA	- Department for Environment, Food and Rural Affairs, United Kingdom
EC	- Eddy Covariance
EPA	- Environmental Protection Agency
ETS	- Emissions Trading Scheme
EU	- European Union
EU15	- European Union prior to the accession of ten candidate countries on 1 May 2004.
EUROFLUX	- European programme measuring carbon dioxide and water vapour fluxes of European forests and interactions with the Climate System
FLUXNET	- A network that coordinates regional and global analysis of observations from micrometeorological tower sites that use eddy covariance methods to measure the exchanges of carbon dioxide (CO ₂), water vapour, and energy between terrestrial ecosystems and the atmosphere.
G	- Soil Heat Flux
GHG	- Greenhouse Gas
GPP	- Gross Primary Production
H	- Sensible Heat
IEA	- International Energy Agency
IPCC	- Intergovernmental Panel on Climate Change
IRGA	- Infrared Gas Analyser
JOULE	- Joint Opportunities for Unconventional or Long-Term Energy Supply, European Union
LAI	- Leaf Area Index
LOI	- Loss Of Ignition
LULUCF	- Land Use, Land Use Change and Forestry
MAFF	- Ministry of Agriculture, Fisheries and Food, United Kingdom

MBM	- Meat-And-Bonemeal
MDV	- Mean Diurnal Variation
NADP-ME	- Nicotinamide Adenine Dinucleotide Phosphate Malic Enzyme
NBP	- Net Biomass Production
NEE	- Net Ecosystem Exchange
NEP	- Net Ecosystem Production
NOAA	- National Oceanic and Atmospheric Administration
NPP	- Net Primary Production
OPW	- Office of Public Works, Ireland
PAR	- Photosynthetically Active Radiation
PPFD	- Photosynthetic Photon Flux Density
PPM	- Parts Per Million
R_a	- Autotrophic Respiration
R_{eco}	- Ecosystem Respiration
REFIT	- Renewable Energy Feed-in-Tariff, Department of Communications, Energy and Natural Resources, Ireland
R_h	- Heterotrophic Respiration
R_n	- Net Radiation
RUE	- Radiation Use Efficiency
SEAI	- Sustainable Energy Authority of Ireland
SOC	- Soil Organic Carbon
SOM	- Soil Organic Matter
SRC	- Short Rotation Coppice
TER	- Total Ecosystem Respiration
UNFCCC	- United Nations Framework Convention on Climate Change
USDA	- United States Department of Agriculture
E	- Constant Activation Energy
ΔE	- Latent Heat
Φ	- Quantum Efficiency

Chapter 1

General Introduction

1.1: Climate Change and Related Policies:

Much of the research into climate change, and alleviating its effects, focuses on the stabilisation of greenhouse gas (GHG) concentrations in the atmosphere. A principal objective of the United Nations Framework Convention on Climate Change (UNFCCC) is to stabilise GHG concentrations at levels that ecosystems can adapt to naturally (Rogner *et al.*, 2007). The three principle GHGs are carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O). These gases occur naturally, but intensive industrialisation has dramatically increased their concentrations in the atmosphere, which has instigated global warming, also termed the 'greenhouse effect' (Intergovernmental Panel on Climate Change (IPCC), 2001). Prior to the Industrial Revolution of the 1790s the CO₂ concentration in the atmosphere remained relatively constant at 275 ppm (parts per million) (Schlesinger, 2003). Subsequently, the advent of large-scale fossil fuel combustion led to a substantial increase in CO₂ concentrations to approximately 385 ppm (Hughes *et al.*, 2010); a concentration exceeding anything experienced on this planet in the past 800,000 years (Lüthi *et al.*, 2008). Over the last three decades atmospheric CO₂ concentrations have increased by 27%. Rising world population, improved living standards and the advancement of technologies have simultaneously increased global energy demands and GHG emissions; each year anthropogenic activities add an extra five billion tonnes of CO₂ to the atmosphere (Acaroğlu and Aksoy, 2005).

The earth's climate is driven by a continuous flow of energy from the sun, about 70 % of which passes into the atmosphere and warms the earth's surface. By the same token, the earth redirects some of this energy back into space in the form of infrared radiation. GHGs act as insulation, blocking the outgoing radiation, and causing an increase in global temperatures (IPCC, 2001). According to Met Eireann, in Ireland the average temperature has increased by approximately 0.7 °C over the last century, with six of the warmest years, since records began, occurring since 1990. It is estimated that temperatures in Ireland will rise by 1.5-2 °C by 2080 (Christensen *et al.*, 2007). The effect of global warming is given as a value of radiation forcing in W m⁻²; the IPCC state that the globally averaged net effect of human activities since 1750 has been one of warming with a radiative forcing of +1.6 W m⁻² (IPCC, 2007). GHGs have different global warming potentials. It is estimated

that CO₂ accounts for approximately 66 % of global warming, while CH₄ and N₂O also contribute greatly to the effect (IPCC, 2007).

Evidence of human interference with the global climate was formally recognised in 1979 at the first World Climate Conference. Thereafter, national Governments grew progressively more aware of climatic issues and in 1988 the IPCC was established with the objective of assessing and summarising scientific information on the subject. A major outcome of the IPCC was the drafting of the UNFCCC. A new treaty extending the remit of the UNFCCC was agreed in Kyoto, Japan in December 1997 and is now commonly referred to as the Kyoto Protocol. This protocol contains several binding commitments. Primarily, the responsibility of wealthier countries to develop 'cleaner' technologies and encourage their uptake in both developed and developing worlds, and the reduction of emissions from six specified GHGs by a minimum of 5.2 % (compared to 1990 baseline estimates) by the period 2008-2012, with demonstrable progress by 2005. Over one hundred and fifty countries have signed the Protocol (representing over 61 % of global emissions); notable exceptions include the USA and Australia. The Kyoto Protocol came into force in February 2005 when the Russian Federation ratified the agreement.

1.2: Ireland's Responsibilities:

Ireland is currently obliged to meet three legally binding targets with respect to reducing GHG emissions. Firstly, through the Kyoto Protocol, where a limitation on Ireland's total national emissions to an average of 62.8 Mt CO₂ equivalents yr⁻¹ in the period 2008–2012 was set, 13 % above the baseline 1990 estimates (Environmental Protection Agency (EPA), 2007). Secondly, under the EU Commission's Energy and Climate Package (EU 2020), agreed by EU Parliament and Council in December 2008, Ireland is required to deliver a 20 % reduction relative to 2005 levels in GHG emissions and simultaneously to increase to 20 % the use of renewable energies. This target is to be reached by 2020 and excludes the sectors covered by the Emissions Trading Scheme (ETS); non-trading sectors include agriculture, transport, and residential areas. Thirdly, the Climate Change Response Act (2010) within the Climate Change Response Bill (Department of the Environment) provides a 2020 GHG emission reduction target, equivalent to an average 2.5 % annual reduction in net emissions between 2008 and 2020. This effectively limits Ireland's total national emissions to an average of 47.7 Mt CO₂ equivalent yr⁻¹. Furthermore, under this bill, Ireland is required to deliver a 40 % reduction in net emissions by 2030 and an 80 % reduction by 2050, relative to 1990 baseline levels.

The principal areas contributing to GHG emissions in Ireland are agriculture, energy and transport. Emissions from agriculture reached a peak in 1998 and have decreased to below their 1990 level over the last few years as a result of the Common Agricultural Policy (CAP), which regulates the use of fertilizer and livestock populations (Styles and Jones, 2007). Ireland is unusual in the European context, with agriculture accounting for 27% of all emissions (EPA, 2007). Emissions of CO₂ from fossil fuel combustion accounted for 68.6 % of total GHG emissions in 2007 compared to 58.5 % in 1990 (EPA, 2007). Over this time, transport showed the greatest increase at 178 % mainly attributed to general economic growth (Figure 1.1).

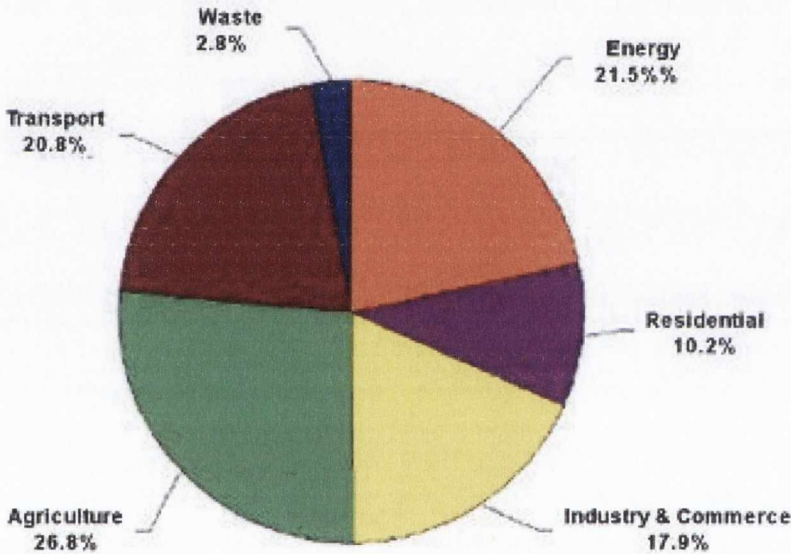


Figure 1.1: Percentages of greenhouse gas emissions produced in Ireland in 2007 by different sectors (taken from EPA, 2009).

In recent years, Irelands’ emissions have come close to 70 Mt CO₂ yr⁻¹, approximately 8 Mt CO₂ yr⁻¹ above the Kyoto 2012 target. In 2008 the EPA projected that Ireland would have to purchase 3.6 Mt CO₂ yr⁻¹ under the terms of the agreement; however, in 2011 accounting for reduced activity due to the slow-down in the national economy, a substantial reduction of more than 50 % on those projections was announced. The purchasing requirement currently stands between 1.3 and 1.6 Mt CO₂ yr⁻¹ over the five year Kyoto period, equating to 6.3 – 8.1 Mt CO₂ (EPA, 2011) (Figure 1.2). The estimated credits acquired by the Irish state are 8.3 Mt CO₂, meaning based on current projections Ireland will have a surplus of 0.1 – 2.0 Mt CO₂ above the national Kyoto commitment. This is a positive outcome in terms of compliance; however, its occurrence is principally due to the current economic downturn. Ireland cannot establish emission reductions on recessions and still requires the development of low carbon economies in order to maintain

compliances in the future (EPA, 2011). Meeting the 2020 targets will be more difficult, as 40 % of emissions originate in the non-trading sector, which is projected to exceed the EU target by 3.8 Mt CO₂ yr⁻¹. In April 2010, projections indicated that non-ETS sector emissions would be 7.6 – 12.4 Mt CO₂ over the 2020 target (EPA, 2011).

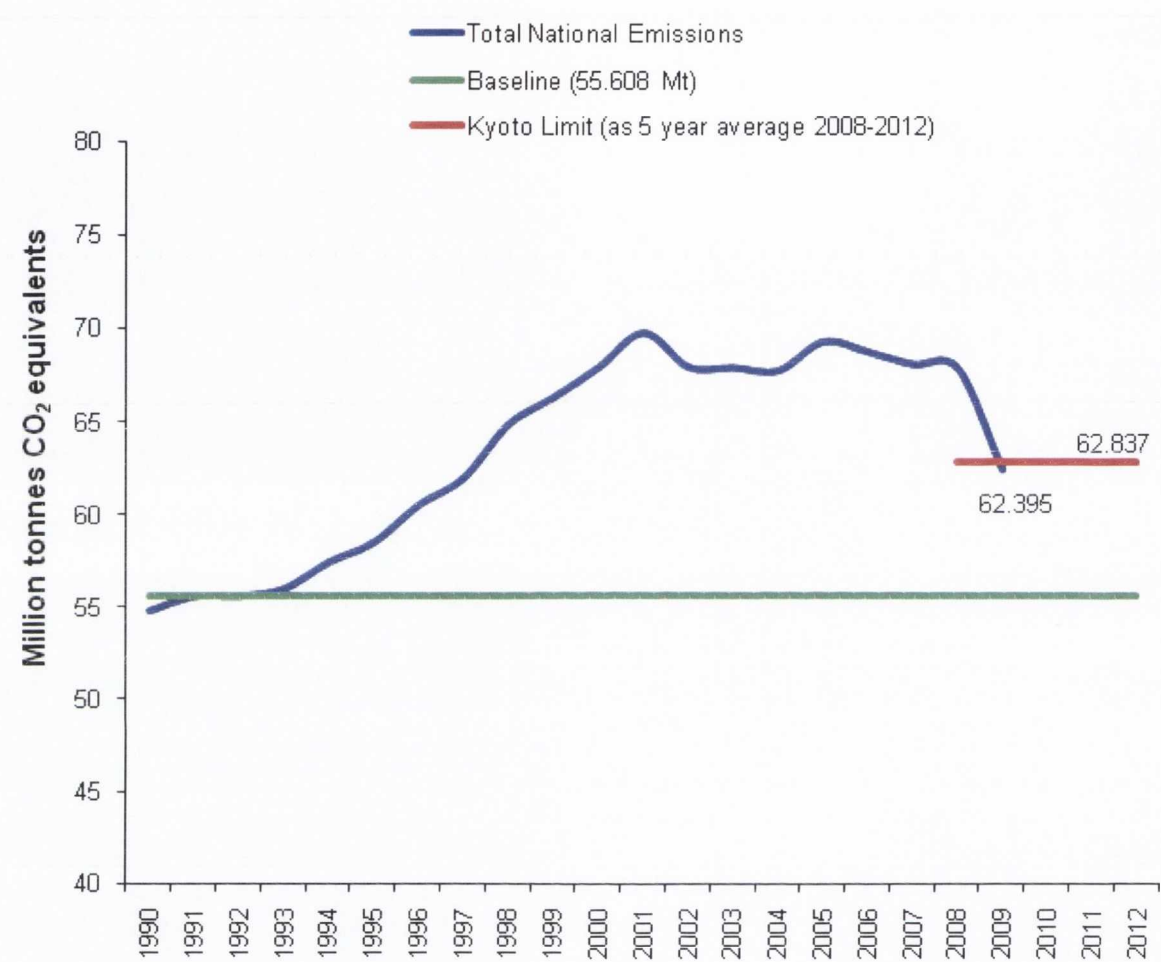


Figure 1.2: Ireland’s greenhouse gas emissions from 1990 to 2010 showing the distance to Ireland’s Kyoto limit and baseline emissions (taken from EPA, 2011).

Under the Kyoto Protocol and EU2020 carbon emissions can be offset by purposefully and demonstrably removing CO₂ from the atmosphere (Schlamadinger and Marland, 2000). Land Use, Land Use Change and Forestry (LULUCF) strategies aim for increased CO₂ storage in vegetation and soils (Article 3.3: Afforestation, Reforestation, Deforestation. Article 3.4: Additional activities) (Watson *et al.*, 2000). Studies suggest that LULUCF strategies may constitute the bulk of GHG emission reductions over the next number of decades (Wigley *et al.*, 1996). This may be a convenient solution in the short or medium

term (IPCC, 2001) but may be unsustainable in the longer-term (Schlamadinger *et al.*, 2001).

The European Environmental Agency (2008) estimates that Ireland can offset 2.1 Mt CO₂ equivalent during 2008-2012 through the creation or enhancement of terrestrial carbon sinks. This value is well above the EU-15 average. LULUCF activities therefore are central to Ireland's strategy for meeting our emission reduction commitments. In general, terrestrial sinks are important components of climate mitigation strategies because, compared to ocean reserves, plant and soil reservoirs respond rapidly to management (Wander and Nissen, 2004). Furthermore, sequestration of carbon into soil is a relatively low cost option for short-term mitigation (Marland *et al.*, 2001). The inclusion LULUCF measures have prompted the current increase in research towards evaluating terrestrial carbon budgets. Countries opting to include changes in land management, grazing management and re-vegetation (under Article 3.4) towards CO₂ mitigation compliance, need to compare the net flux of carbon from a given activity during the commitment period with the equivalent net flux of carbon in the baseline year (1990). One of the best prospects for climate change abatement through changes in agricultural practices is in the form of perennial grasses grown for biofuel (Wander and Nissen, 2004). This study investigates the potential of growing the bioenergy crop *Miscanthus x giganteus* on Irish arable land as a means of contributing towards our national CO₂ abatement targets.

1.3: Biomass and Bioenergy:

Biomass is a term for all organic material produced by chlorophyll-containing organisms (including plants, algae and some bacteria) (McKendry, 2002). Biomass production is based on the storage of energy from sunlight into chemical bonds between carbon, hydrogen and oxygen through the photosynthetic process. Virtually, all energy for life in the earth's biosphere is made available through photosynthesis (McKendry, 2002). Globally, biomass has always been a major source of energy and currently accounts for approximately 10-14 % (50 EJ yr⁻¹) of the total world need (406 EJ yr⁻¹). The use of biomass is essentially based on agro-forestry residues and natural forests, predominately in developing countries, but more recently there is increasing interest in utilizing biomass in the developed world.

Bioenergy, energy sourced from biomass, is considered to be an appealing option for energy production at a national and global-scale (van den Broek *et al.*, 1995). The use of

bioenergy reduces dependencies on fossil fuels, decreases CO₂ emissions and has the associated benefits of climate change abatement and energy sustainability. It is predicted that global bioenergy production will quadruple by 2030 (Fairless, 2007). Cannell (2003) estimated that by developing energy cropping systems, at a world wide scale (200 to 400 Mha) over a long term (50 to 100 years), the carbon emissions into the atmosphere could be reduced by 1000 to 2000 Mt C yr⁻¹. The extent to which bioenergy crops impact the global carbon cycle depends upon their overall relative efficiency of biomass production and utilisation (Sartori *et al.*, 2006). Sims *et al.* (2006) estimated that between 2 and 22 EJ yr⁻¹ of energy could be produced by energy crops. However, it is possible that the EU and USA will have insufficient suitable available land area to achieve future bioenergy targets and may rely on developing countries for this resource (Gibbs *et al.*, 2008; IEA, 2006).

Burning fossil fuels releases 'old' stored carbon into the atmosphere, contributing to the 'greenhouse' effect and depleting non-renewable resources. Burning new biomass contributes no additional CO₂ to the atmosphere, as only contemporary carbon, fixed through photosynthesis, is released upon combustion (i.e. a carbon neutral form of energy) (McKendry, 2002). Bioenergy crops also contribute to the mitigation of net CO₂ emissions by enhancing sequestration of carbon in the underlying soils (Matthews and Grogan, 2001). For this reason, purpose-grown carbon neutral energy crops will play a key role in meeting the CO₂ emission reduction objectives (Fischer *et al.*, 2005).

Smith *et al.* (2000) have examined agricultural options for carbon mitigation across Europe and concluded that bioenergy crops, grown on surplus arable land, show the greatest potential. These calculations were based on both the direct substitution of fossil fuels and on carbon sequestration in the soils (Foereid *et al.*, 2004). In conjunction with CO₂ emission reductions and carbon sequestration, the establishment of energy crops has several extra advantages. Energy crops have shown higher productivity per land unit than their conventional counterparts (Jasinskas *et al.*, 2008; Panoutsou, 2007). Many of the agricultural crops require high inputs of nitrogen in fertilizers or manure, which gives rise to nitrous oxide emissions; however, energy crops, and perennial grasses in particular, require far fewer inputs. Moreover, the elimination of annual cultivation reduces soil erosion, which is beneficial for biodiversity, increases soil organic matter content and improvements in soil quality (Powlson *et al.*, 2005, Lewandowski and Schmidt, 2006). The development of renewable energy sources plays an important role in reducing GHG emissions through decreased disturbance frequencies, increased quantity and duration of

plant cover and ameliorated nutrient deficiencies, all of which increase soil carbon sequestration levels (Wander and Nissen, 2004). For these reasons bioenergy crops are receiving considerable interest as a potentially low-cost, carbon-neutral renewable source of energy.

1.4: The Current Situation in Ireland:

Currently over 90 % of Irish energy requirements are imported. Our lack of indigenous energy, our peripheral geographical location and small market leaves Ireland vulnerable to supply disruption and imported price volatility (White Paper, 2007). From an economic perspective, it is imperative that Ireland obtains secure and dependable sources of fuel at reasonable costs. The land area of Ireland is approximately 7 million hectares, of which 4.3 Mha is used for agriculture and approximately 710,000 ha for forestry. Grasslands supporting livestock account for 83 % of agricultural land area (3.4 Mha) (McGettigan *et al.*, 2006), and emit substantial quantities of potent GHGs (Styles and Jones, 2007). The decoupling of EU agricultural supports has markedly reduced earnings from conventional farming practices (mainly dairy, beef and sheep farming) and now many Irish farmers are looking for alternative land uses with better financial returns (Hennessy and Thorne, 2006). Increasing energy prices and the necessity to reduce GHGs has directed their attention towards energy crops. Ireland also has a surplus of land in set-aside (*c.* 30,000 ha) that is unsuitable for many farming practices but could be used to grow energy crops. However, it should be recognised that set-aside land, by its nature, is marginal and often small in area; it is anticipated that approximately 10,000 ha would be viable for energy crop production (Bioenergy Action Plan, 2007). The ending of sugar beet farming in Ireland in 2006 has also released some 31,000 ha of tillage land, which is potentially available for energy crops.

Rice (2003) suggested that biomass crops in Ireland have an energy yield ranging between 100 to 200 GJ ha⁻¹, although this is dependent on several factors including crop selection, land quality and climatic conditions. Assuming an average energy yield of 125 GJ ha⁻¹ could be achieved, an area of over 0.5 Mha would be required to produce 10 % of Ireland's national primary energy requirement, representing more than the current land area under arable management. Therefore, it is apparent that biomass crops have the potential to become substantial suppliers of energy to the Irish market, but that large areas of land would have to be diverted from the traditional activities to achieve this. Previous studies in Ireland, looking at electricity production from biomass have concluded that energy crop

biomass is an expensive source of electricity (van den Broek *et al.*, 1997; 2001) and financially compares poorly with forestry residues and wastes. However, in the present environment of increasing fuel prices and decreasing farm incomes, energy crops have become a more attractive option (Styles and Jones, 2007). Renewable energy sources are also indigenous and can play a key role in decreasing dependency on imported energy (Fischer *et al.*, 2005); encouraging regional development and job creation which is especially important in rural areas as they often suffer from high unemployment. Moreover, renewable energies can generate niche markets that could greatly benefit small and medium sized enterprises.

The Irish Government introduced a range of measures to encourage the development and deployment of renewable sources of energy, including the REFIT scheme, the mineral oil tax exemption scheme, the Greener Homes scheme, and combined heat and power (CHP) support programmes. Under the National Development Plan 2007-2013, through Sustainable Energy Programmes and Schemes, at least 270 million euro will be invested into the sector (White paper, 2007). Furthermore, the office of public works (OPW) is developing a 'New Building' programme whereby bioenergy-heating systems will become standard in all new OPW buildings and large existing State buildings will be converted to bioenergy heating systems (Bioenergy Action Plan, 2007). In addition, according to the Food Harvest 2020 report (Department of Agriculture, Food and the Marine, 2010), which outlines the actions required to ensure Irish economic recovery and the development of a smart economy, bioenergy crops were identified as playing a key role in Ireland's medium-term agricultural development for the period to 2020. The Food Harvest 2020 report recommended the continuation of financial supports in the bioenergy sector, the development of supply chain mechanisms to ensure full market returns, encouragement of new entrants into the sector through an intensive marketing campaign and the further research by Teagasc into bioenergy crop development. Despite considerable effort to promote bioenergy crops, implementation is still rather slow across Europe (European Commission, 2000; 1997). Large initial capital investment costs for producers, in conjunction with market uncertainties and some negative perceptions of energy crops are considered the major barriers to their development (Styles and Jones, 2007; Sherington and Moran, 2010; Sherington *et al.*, 2008).

1.5: The Global Carbon Cycle:

The global carbon cycle is a term used to describe the movement of carbon, in a variety of forms, through oceanic, terrestrial and atmospheric ecosystems (Sartori *et al.*, 2006; McCarthy *et al.*, 2001). The cycle is driven by a combination of biotic, abiotic and anthropogenic activities. Fluxes from the cycle occur over a large temporal scale. Over millions of years, carbon cycling is controlled by the burial of carbon into the Earth's crust and the release through tectonic movements; over seconds, carbon cycling is driven by surface-air exchanges through photosynthesis and respiration (Chapin *et al.*, 2002). Oceans account for approximately 38,000 Gt C, the majority of which (98 %) is in an inorganic form, predominately as HCO_3^- ; dissolved organic and inorganic carbon account for the remaining 2 % (Chapin *et al.*, 2002). Soil organic matter (SOM) represents the largest terrestrial carbon pool (approximately 1,500 Gt C) while carbon stored in biomass accounts for 500 Gt C (IPCC, 2001). Atmospheric carbon (approximately 730 Gt C) is mainly in the form of CO_2 but methane (CH_4), carbon monoxide (CO) and various volatile organic carbon forms also contribute to the C pool. In addition, sedimentary rocks contain high levels of carbonates; tectonic activities, volcanism and weathering are important in releasing this lithogenic carbon into the global C cycle.

Prior to human interference the global carbon cycle was in a close state of equilibrium; the net release of carbon into the atmosphere was balanced by net sequestration rates (Schlesinger, 2003). This delicate balance was initially disrupted through increased GHGs emissions resulting from human activities; for instance, the combustion of wood and fossil fuels, the conversion of forested areas to agricultural land and the use of plant biomass for construction (Osmond *et al.*, 2004; Kammen and Marino, 1993). The imbalance was further worsened by the Industrial Revolution of the 1790s and the start of large-scale fossil fuel combustion (Hughes *et al.*, 2010).

1.6: Carbon Cycling in Terrestrial Ecosystems:

The main input of carbon into terrestrial ecosystems is via photosynthesis. The conversion of atmospheric CO_2 into carbohydrates through photosynthesis is termed gross primary production (GPP). These carbohydrates can be used to form new plant tissues during growth or metabolised and returned to the atmosphere through autotrophic respiration (R_a). Net Primary Production (NPP) is defined as the difference between photosynthetic gain and plant respiratory losses ($\text{NPP} = \text{GPP} - R_a$). Carbon is also lost from an ecosystem through heterotrophic respiration (R_h). Collectively the lost carbon from an ecosystem

through respiration is termed ecosystem respiration ($R_{eco} = R_a + R_h$). Net Ecosystem Production (NEP) is defined as GPP less R_{eco} ($NEP = GPP - R_{eco}$); however, this calculation ignores additional carbon losses not associated with respiration. Carbon can be exported from a system through harvesting, leaching, erosion, herbivory and losses from fire. The impact of leaching dissolved carbon is often ignored and may result in an over-estimation of the carbon storage (Siemens, 2003). Net Biome Production (NBP) provides an ultimate measure of the carbon budget of an ecosystem, accounting for both respiratory and non-respiratory losses ($NBP = NEP - \text{non-respiratory losses}$). NBP, in effect, defines the carbon sink or source strength of an ecosystem. A simplified overview of the processes within a terrestrial carbon cycle is presented in Figure 1.3.

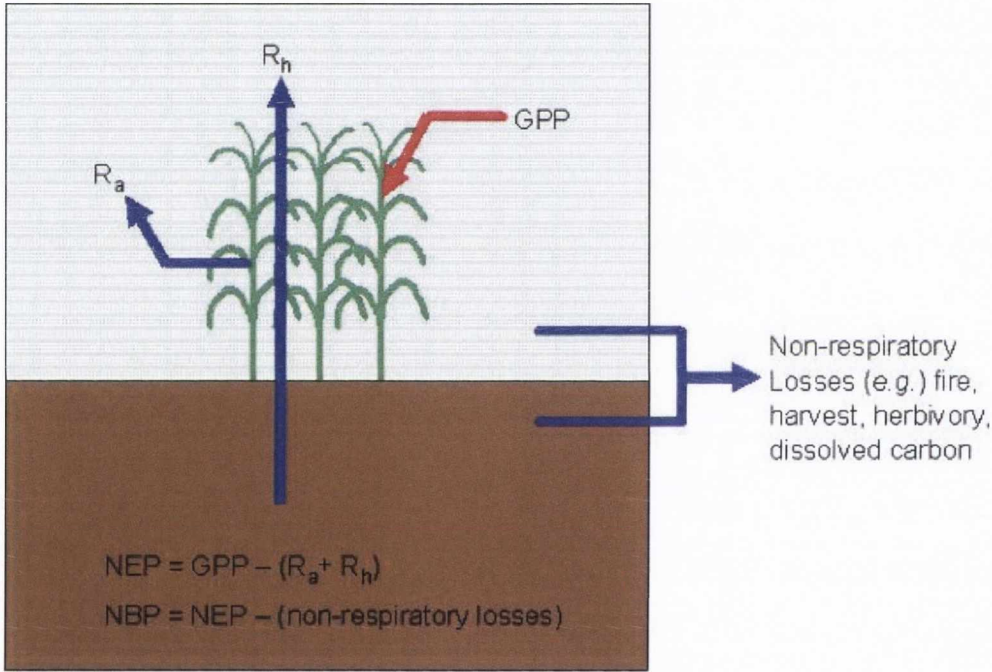


Figure 1.3: A simplified overview of the processes involved in a terrestrial carbon cycle. GPP = Gross Primary Production, R_a = Autotrophic Respiration, R_h = Heterotrophic Respiration, NEP = Net Ecosystem Production, NBP = Net Biome Production. Non-respiratory losses include processes such as harvesting, fire, leaching and grazing (this list is not comprehensive).

Information regarding carbon cycles has markedly increased over the past two decades, owing to the rise in international awareness of climate change and GHGs (Running *et al.*, 1999; Ruimy *et al.*, 1995; Crill, 2009). The quantification of carbon sink or source strengths is crucially important in furthering our understanding of the roles ecosystems play in carbon mitigation and assisting in future land-use management strategies (van Hees *et al.*, 2005). Remote sensing, air sampling networks, and eddy covariance measurements

are common techniques employed to record carbon concentrations and fluxes which vary greatly in spatial and temporal resolutions (Canadell *et al.*, 2000). These direct measurements are often time consuming and costly; therefore, up-scaling and modelling field level chamber measurements are also regularly used. A combination of eddy covariance and chamber measurements were used in this study to provide a detailed understanding of the terrestrial carbon fluxes within a *Miscanthus x giganteus* stand.

1.7: *Miscanthus x giganteus*:

Miscanthus x giganteus is a woody, rhizomatous grass with near-ideal characteristics for bioenergy production (Nixon and Bullard, 2001), namely perennial growth, C4 photosynthesis, high dry matter yields, high water and nutrient-use efficiencies, and good disease and pest resistances. *M. giganteus* was first introduced into Europe in 1935 as an ornamental plant from South East Asia (Lewandowski *et al.*, 2000). The first trial on growing the crop for energy and pulp production was carried out in Denmark in the late 1960s (Venedaal *et al.*, 1997). In 1989, based on promising preliminary results, the European JOULE research programme funded the establishment of several additional *M. giganteus* plantations in Denmark, Ireland, the UK and Germany. The interest generated by these early field studies lead to the increased distribution of trials to Southern Europe under the European Agro-Industry (AIR) programme (Lewandowski *et al.*, 2003). Under AIR, the European *Miscanthus* Network was launched in 1992 with the expressed aim of investigating the potential of *M. giganteus* as a biomass crop and as a source of raw material for industries. In 1997, under the *Miscanthus* Productivity Network, a project began to develop new hybrids, improve breeding methods and screen genotypes across Europe. More recently, trials to assess the suitability of *Miscanthus* in North America have commenced (Heaton *et al.*, 2010).

1.7.1: Genetics of *Miscanthus*:

According to Deuter (2000), the genus *Miscanthus* consists of seventeen species, which can be divided into four categories: *Kariyasua*, *Diandra*, *Thiarrhena* and *Eumiscanthus*, only the latter two containing genotypes of interest to biomass production. The genotype widely used in productivity trials is *M. giganteus* (Greef & Deuter ex Hodkinson & Renvoize) (Hodkinson *et al.*, 2002), a sterile triploid with fifty-seven chromosomes. It is a natural hybrid of *M. sacchariflorus* (diploid, member of the *Eumiscnathus*) and *M. sinensis* (tetraploid, member of the *Thiarrhena*) (Hodkinson *et al.*, 2002). *M. giganteus* is more vigorous than its parental plants, with enhanced stress tolerances (Heaton *et al.*, 2004).

Scally *et al.* (2001) suggest that *M. giganteus*, which is found in a wide range of climates from tropical to sub-tropical and temperate regions in East Asia (Stewart *et al.*, 2009; Lewandowski *et al.*, 2003), retains high productivity in both warm and cool climates due to the genetic contributions from its' parents. The *M. sacchariflorus* genes allows for growth in warmer climates and *M. sinensis* provides the genetic resources for cooler regions.

Until recently, only a single clone of *M. giganteus* was widely used in field trials throughout Europe (Clifton Brown and Lewandowski, 2000) originating from trials in Hornum, Denmark (Jørgensen and Schwarz, 2000). There are a number of disadvantages associated with relying on a single clone, namely the high risk of rapidly spreading diseases and pests. Also, there are considerable limitations in the ability of a clone to adapt to a variety of climatic and edaphic conditions (Hodkinson *et al.*, 2002). During field trials, *M. giganteus* displayed a number of location-specific problems across Europe, including: poor establishment and over-wintering rates (Jorgensen *et al.*, 2003, Clifton Brown and Lewandowski, 2000a), low water-use-efficiencies (Clifton Brown and Lewandowski, 2000b) and reduced combustion qualities (Clifton Brown *et al.*, 2001).

1.7.2: The perennial growth cycle of *Miscanthus*:

M. giganteus, hereafter referred to as *Miscanthus*, has a cyclical growth pattern. Following the planting of rhizomes, multiple shoots develop from late April onwards. The shoots appear once accumulated daytime temperatures exceed approximately 200 to 400 °C (Bullard and Nixon, 1999). These shoots develop into erect, unbranched, bamboo-like canes, with a diameter approximately 20 mm, reaching a height of 1 to 3 m by late August (Caslin *et al.*, 2010). In July, full radiation interception is achieved by the canopy and the lower leaf layers begin to senesce, whilst shoot growth continues until late September or early October (Nixon and Bullard, 2001). Following the first frost senescence accelerates. Leaves fall from the stems and by February the stems are almost leafless. The standing biomass gradually dries over winter, ready for harvest in late spring. The growth cycle is repeated once spring temperatures reached the threshold again (Plate 1.1).

Plate 1.1: The life cycle of *Miscanthus* from May to April. Photos taken in Oak Park Research Centre, Co. Carlow.



May: New *Miscanthus* stems emerge



July: *Miscanthus* over 1 m tall



September: Maximum growth, lower leaves senesce



October: Some plants exhibit sterile inflorescence



November: Leaves senesce



December: Complete senescence



February: Leaves fall from stems



April: Crop is harvested



April: Bales left to air dry



April: Field following harvest

Miscanthus grows in a variety of locations with varying soil types but favours soils with high water-holding capacities and high organic matter contents (Christian and Haase, 2001). It is also tolerant to a wide range of pH values, but the optimum range is 5.5 to 7.5 (Finch *et al.*, 2009). However, *Miscanthus* does not have sufficient rhizome cold tolerance in its first year to survive severe winters with soil temperatures below -3°C (Clifton Brown and Lewandowski, 2000).

Miscanthus spreads naturally by means of rhizomes. This spread is very slow and there is negligible risk of an uncontrollable invasion. There are two main methods of propagation currently used: rhizome division and micro-propagation (Ministry of Agriculture, Forestry and Fisheries (MAFF), 2000; Bullard, 1996). No discernible differences have been recorded in establishment rates between the two techniques. However, micro-propagation is up to five times more expensive (Venturi *et al.*, 1999) and is no longer recommended by Department of the Environment, Food and Rural Affairs (DEFRA) (2001) in the UK. A third, less used, propagation method is stem rooting. Under suitable conditions *Miscanthus* stems, at nodes one and two, are capable of producing propagules with both root and shoot development (MAFF, 2000). Major developments in *Miscanthus* planting techniques, especially the introduction of specific rhizome planting machines, dramatically reduced

costs and achieved reliable crop emergence (Nixon *et al.*, 2001; Lewandowski *et al.*, 2003). A target-planting rate of 20-30,000 rhizome ha⁻¹ is recommended to achieve high established yields (Caslin *et al.*, 2010). Establishment costs are quite high for *Miscanthus*, primarily due to the cost of the rhizomes. In addition, despite the proceeds from forestry being tax-free, profits from *Miscanthus* are still taxed and Capital Allowances are not applicable despite the long life cycle of the crop (Doyle, 2011). Financial support is currently available through the BioEnergy Scheme administered by the Department of Agriculture, Fisheries and Food (DAFF) with establishment grants and subsidies (DAFF, 2007). The crop is also eligible for an Energy Aid payment when grown on non set-aside lands. Styles and Jones (2007) demonstrated that, at 2007 prices, *Miscanthus* cultivation could be economically competitive with other agricultural land-uses at a farm-gate price of 70-130 euro t DM. Since 2007 a total of 2,475 hectares (6115 acres) of *Miscanthus* have been planted under the DAFF Bioenergy Scheme; as of 2010 the quantity of *Miscanthus* grown in Ireland should provide approximately 445,424 GJ of energy, enough to heat 6,000 average homes (Caslin *et al.*, 2010). One hectare of *Miscanthus* provides approximately 164 GJ of energy, in comparison, 1,000L of oil contains 36.68 GJ.

There is much debate regarding the most favourable harvesting period for *Miscanthus*. Ultimately, the biomass producer faces a trade-off between optimising crop quantity and quality (Heaton *et al.*, 2004; Lewandowski and Heinz, 2003). The decision requires a balance between moisture content, crop yields and combustion characteristics. Generally, *Miscanthus* is either harvested in late autumn (Early Harvest) or early spring (Late Harvest). Yields are greatest when *Miscanthus* is harvested early; delaying the harvest results in a substantial loss of leaves and upper stems which causes a large reduction in dry matter by as much as 30-50 % (Jorgensen, 1997). Field trials in Central Europe show a linear relationship between yield losses and the length of time between early and late harvests (0.36 % per day delay in harvest time), in Ireland losses of 0.3 % per day delay in harvest time were recorded in Cashel, Co. Tipperary (Clifton Brown *et al.*, 2001). The main benefit of delaying crop harvest is the significant decrease in moisture content of the standing biomass, up to 25 % (Heaton *et al.*, 2008). Low water content is important for both the storability and combustion of the crop. A maximum limit of 23 % water content is required for the safe storage of *Miscanthus* (Ercoli *et al.*, 1999). Moreover, excessive water concentration lowers the heating value and also increases the flue gas volume, which collectively decreases combustion efficiency (Lewandowski and Kircherer, 1997). Transport costs rise considerably with increasing water content. If necessary, *Miscanthus*

can be dried artificially. Drying the crop can be an expensive process. Van den Heuve (1995) determined a cost of 3.7, 12.0 and 31.2 euro t⁻¹ DM for drying *Miscanthus* to a moisture content of 15 % from initial values of 30, 50 and 70 % moisture, respectively.

Studies have shown that delaying the harvest time for *Miscanthus* improves the combustion quality of the crop (Lewandowski *et al.*, 2003). Good biomass combustion depends on minimizing moisture, ash, potassium (K), chlorine (Cl), nitrogen (N) and sulphur (S). As the standing biomass dries over the winter months the Cl, K and ash components are gradually leached from the shoots by precipitation, while N and K concentrations are decreased through translocation into the rhizomes and leaf senescence (Lewandowski *et al.*, 2003). The stem components of *Miscanthus* have the best firing properties of the plant (Monti *et al.*, 2007). A drawback to the combustion of *Miscanthus* is the low ash melting point of the biomass, which can be problematic in some boilers. It is thought that this trait is attributable to high silica and K levels in the crop. Lewandowski and Kicherer (1997) suggest that it may be possible, in the future, to alter the content of these elements through new agricultural methodologies.

1.7.3: C4 Photosynthesis and High Biomass Yields:

Miscanthus has the C4 photosynthetic pathway (NADP-ME form) (Naidu *et al.*, 2003). The C4 pathway is more efficient at converting CO₂ into stored biomass than the more common C3 pathway, inherent in most agricultural crops of temperate regions (Styles and Jones, 2007). C4 photosynthesis allows for maximum conversion of intercepted solar radiation into biomass energy by concentrating CO₂ around Rubisco and by largely eliminating photorespiration (Heaton *et al.*, 2004). The gain in radiation use efficiency (RUE) conferred by C4 photosynthesis can be as much as 40 % over the conversion rate in C3 plants (Long, 1999). In contrast to many other C4 species *Miscanthus* can also achieve and maintain high CO₂ assimilation rates under cool conditions (Naidu and Long, 2004; Farage *et al.*, 2006). Numata (1979) suggests this is due to *Miscanthus* naturally occurring and adapting to cooler climates. RUE depends greatly on the duration, size and structure of the canopy; *Miscanthus* has an ideal canopy to maximise radiation interception by developing a dense canopy of rapidly growing leaves (Beale and Long, 1995; 1997). At its optimum, *Miscanthus* can achieve a leaf area index (LAI) of 7 - 8 (Atkinson, 2009). Once the sunlight energy is captured, *Miscanthus* can maintain high rates of photosynthesis (approximately 20 μmol CO₂ m⁻² s⁻¹) (DEFRA, 2002), resulting in the rapid growth of the

plant during the growing season (up to $50 \text{ g m}^{-2} \text{ day}^{-1}$) (Bullard *et al.*, 1995; Beale and Long, 1995).

Miscanthus is a high yielding crop due to its high photosynthetic abilities. There is a large body of data relating to biomass yields for *Miscanthus*, as productivity is essential when considering its viability as an energy crop (Beale and Long, 1995; Clifton-Brown *et al.*, 2000; Schwarz, 1993; Hotz, 1996; Himken *et al.*, 1997; Venendaal *et al.*, 1997; Heaton *et al.*, 2009). Within the published literature, annual dry matter yields vary considerably but range from approximately 5 to 55 t DM ha⁻¹ (Heaton *et al.*, 2010; Lewandowski *et al.*, 2000, 2003; Atkinson, 2009; Jones and Walsh, 2001). Modelled and measured yields in Ireland are considerably lower (10-26 t DM ha⁻¹ yr⁻¹) (Clifton Brown *et al.*, 2000), with the highest predicted yields occurring in the south-west of the country. *Miscanthus* normally requires 2 - 3 years to establish, after which cropping is annual for approximately fifteen years. The yield in the first season's growth (approximately 1 - 2 t DM ha⁻¹) is not usually harvested. Harvestable yields in year two range from 4 - 10 t DM ha⁻¹ (Lewandowski *et al.*, 2003).

Miscanthus also produces considerable below ground biomass. The root system allows for the sequestration of carbon into the soil as well as providing increased resistance to soil erosion (Heaton *et al.*, 2004). There is some variation within the literature, but between 13 - 25 t DM ha⁻¹ can be found in mature below ground structures (Kahle *et al.*, 2001; Clifton Brown *et al.*, 2007; Hansen *et al.*, 2004; Himken *et al.*, 1997; Beuch, 1995). This amounts to approximately 6 - 12 t C ha⁻¹, which can increase substantially over time. Using the Matthews and Grogan (2001) model, Clifton Brown *et al.* (2001) predicted that soil organic carbon (SOC) accumulation rates of 0.86 t C ha⁻¹ yr⁻¹ could be expected under Irish *Miscanthus* plantations on previously tilled soils. Dondini *et al.* (2009) predicted that in Ireland, changing the land use from arable to *Miscanthus* plantations had the potential to store between 2 - 3 t C ha⁻¹ y⁻¹ depending on the crop yield and the initial SOC content. While King *et al.* (2004) demonstrated that the conversion of arable land to *Miscanthus* resulted in an increase in SOC of 0.49 - 0.73 t C ha⁻¹ yr⁻¹, but the conversion of grassland to *Miscanthus* cannot be expected to change SOC. Davis *et al.* (2010) stated that in the case of arable displacement, there was a net increase in carbon sequestration due to the fact that arable soils have low carbon contents. Increases in SOC are linked to improved soil texture, water retention and greater fertility (Rowe *et al.*, 2007). Importantly, Schneckenberger and Kuzyakov (2007) showed that *Miscanthus*-derived carbon had a

higher contribution to SOC in deeper soil layers compared to maize; this underlines the strong potential of belowground C sequestration by planting *Miscanthus* stands. It has been reported that 8.8 t C ha⁻¹ has been stored in the roots and rhizomes of a *Miscanthus* stand over the twelve years of its life.

1.7.4: Water and Nutrient Use Efficiency:

C4 plants in general have low water consumptions. Dressler and Herzog (2004) demonstrated that only 270 - 300 litres of water kg⁻¹ DM are necessary for *Miscanthus* growth. This is almost half the amount of water required by cereal crops and a third of that needed by coppice plantations (Lewandowski *et al.*, 1995). *Miscanthus* has deep roots that can penetrate and extract water from soils to a depth of approximately 2 m. This is particularly important as, once the crop reaches canopy closure, 20 - 30 % of all rainfall is intercepted and evaporated off the leaves, never infiltrating down to the soil. Limited soil water availability can significantly reduce yields. Caslin *et al.* (2010) estimated a loss of 90 kg of biomass ha⁻¹ for each mm of soil water deficiency. In field studies annual differences in harvested biomass yields are mainly attributed to moisture stresses (Price *et al.*, 2004; Nixon and Bullard, 2001).

Miscanthus has a high nutrient cycling efficiency, compared with arable crops such as wheat and barley (Styles and Jones, 2007). At the end of the growing season nutrients in *Miscanthus* are translocated from above ground plant parts to the rhizome. There is also a significant return of plant nutrients through the decomposition of leaf litter. For these reasons, nutrient off-take is very low. The nutrients are stored in the rhizome during the winter and reused to support early growth of shoots in the following spring (Caslin *et al.*, 2010). In Europe, fertilisers are not needed on *Miscanthus* stands in the first two years of growth, unless soils are extremely nutrient-poor, as there are sufficient nutrients in the soil (McKervey *et al.*, 2008). Application of fertilisers at this time would only encourage weed growth. In the third, and subsequent years, fertiliser applications are low: 40-100 kg ha⁻¹ N, 10-20 kg ha⁻¹ P, and 40-100 kg ha⁻¹ K (Christian and Haase, 2001; Heaton *et al.*, 2004; Beale and Long, 1997; Himken *et al.*, 1997).

1.7.5: Disease and Pest Resistance:

Miscanthus species are susceptible to pests and diseases in their native environments. A number of invertebrates have also been found living on *Miscanthus* in field trial studies around the world (*Rhopalosiphum maidis*, *Sipha flava*, *Mesapamea secatis*, *Diabrotica*

virgifera virgifera, *Spodoptera frugiperda*) but none, other than *Spodoptera frugiperda*, have reduced harvestable biomass (Bradshaw *et al.*, 2010; Prasifka *et al.*, 2009; Spencer and Raghu, 2009; Huggett *et al.*, 1999). Herbivory is rarely an issue, apart from possible rabbit grazing of newly emerged shoots during the establishment phase. Disease and pest pressures may increase with large-scale productions over time.

1.7.6: The Effect of *Miscanthus* on Biodiversity:

Increased interest in the production of energy crops, at a commercial scale, is likely to lead to marked changes in the Irish arable landscape, as large areas of farmland are converted to bioenergy crops. Investigations into the environmental impacts of such a land-use change are essential (Semere and Slater, 2007a). The difference in crop structure and management, between *Miscanthus* and conventional arable crops, has led to speculation that wide-scale plantations may have significant effects on wildlife biodiversity (Bellamy *et al.*, 2009). The findings from several biodiversity studies indicate that the introduction of *Miscanthus* into the Irish countryside may potentially provide substantially improved habitats for native wildlife; although, the effects of species populations will depend strongly on which arable crops are replaced and the area of new plantations. Results also highlight the importance of field margins and boundaries in the abundance and range of plants and animals. Similar findings were reported by Fennelly (2009), implying a strong necessity to retain traditional field structures when planting energy crops (Semere and Slater, 2007b). Dauber *et al.* (2010) showed that replacing traditional crop types with *Miscanthus* did not result in an obvious negative impact on biodiversity at field scale; however, they highlighted that the large-scale planting of *Miscanthus* may reduce overall landscape heterogeneity, which could result in biodiversity losses at the landscape scale. Mixtures of various perennial grasses may encourage increased biodiversity, whilst improving the public acceptance of bioenergy production by contributing to the visual diversity of the landscape (Lewandowski *et al.*, 2003). Ecosystem management will be required to maintain biodiversity throughout the lifespan of the *Miscanthus* crop, especially if agricultural practices intensify in order to maximise crop yields (Bellamy *et al.*, 2009). The impact of removing *Miscanthus* and converting to another crop must also be considered. Anderson *et al.* (2010) reported that a stand could be successfully removed through a combination of tillage and glyphosate applications; however, it is likely that more than two growing seasons are needed for full eradication.

In summary, *Miscanthus* has many characteristics of an ideal bioenergy crop, with high photosynthetic capacities, high crop yields, perennial growth, deep roots, low nutrient and water requirements, high disease and pest resistance and a low risk of becoming invasive. Heaton *et al.* (2004) compared several crop characteristics between corn, short-rotation coppice and *Miscanthus* to highlight the positive attributes of *Miscanthus* over conventional crops; this comparative study is summarised in Table 1.1.

Table 1.1: Comparing characteristics of an ideal bioenergy crop between corn, short rotation coppice (SRC) and *Miscanthus* (taken from Heaton *et al.*, 2004). + means the trait is present in the crop.

Crop Characteristic	Corn	SRC	<i>Miscanthus</i>
C4 photosynthesis	+		+
Long canopy duration		+	+
No known pests or diseases			+
Rapid growth in spring to out compete weeds		+	+
Sterile: prevents ‘escape’			+
Stores carbon in soil		+	+
Partitions nutrients back into roots			+
Low nutrient content (clean burning)		+	+
High water use efficiency	+		+
Dries in field (zero drying costs)			+
Good winter standing (zero storage costs)		+	+
Utilises existing farm equipment	+		+
Alternative markets (paper, building materials, fermentation etc)	+	+	+

1.7.7: The Use of *Miscanthus* in Ireland as a Bioenergy Crop:

The most likely end-use of *Miscanthus* is the energy market, although, the crop has been used successfully for paper production, medium density fibreboards, animal bedding material and as a growing medium/soil improver. At present, combustion provides the primary pathway for converting *Miscanthus* into energy, but technologies that allow for conversions into liquid biofuels are developing and will soon become commercially viable (Caslin *et al.*, 2010). *Miscanthus* has a high-energy-ratio, whereby the energy expended in growing is much less then that released when used as a fuel. The environmental

consultancy agency ADAS, on behalf of the Department of Trade and Industry in the UK, gave *Miscanthus* an energy ratio of 53:1, for every one part of man-made carbon input needed by the plant to grow, 53 parts are absorbed by the crop from the environment. Harvey (2007) described the energy ratios for a number of energy crops, a summary of his findings is provided in Table 1.2.

Table 1.2: The energy ratios for a number of energy crops (from Harvey, 2007).

Crop	Energy In (MJ ha ⁻¹)	Energy Out (MJ ha ⁻¹)	Ratio
<i>Miscanthus</i>	9,224	300,000	32.5
Willow (SRC)	6,003	180,000	30.0
Hemp (straw)	13,298	112,500	8.5
Wheat (grain)	21,465	189,338	8.8
Oilseed rape	19,390	72,000	3.8

The co-firing of *Miscanthus* with peat is probably the most realistic use of the crop for electricity generation (van den Broek *et al.*, 2001). In Ireland, the comparatively high dependence on peat and coal power stations offers a strong potential for a direct substitution with renewable biomass, as capital investment costs would be minimal (Styles and Jones, 2007). Additionally, increasing political and public dissatisfaction with damaging finite, ecologically important peat bogs has prompted debate in reducing our peat reliance. The Bord na Mona Power Station at Edenderry has begun combusting wood chip and meat-and-bonemeal (MBM) in conjunction with peat burning. The true opposition to viably using *Miscanthus* as a fuel is the current inability of the crop to successfully compete against cheaper alternative energy sources, such as forest thinnings or MBM, which is a free agricultural waste product. *Miscanthus* does have some advantages over the cheaper alternatives; it is a high yielding crop with shorter harvest intervals than forestry (Styles and Jones, 2007); it can be cultivated close to the end-user, thereby reducing expensive transport requirements; it is a predictable and reliable source of biomass over it's life cycle.

In Ireland, most of the oil and gas, and some of the electricity, is used for heating space and water. There is a large market for biomass heat, in the form of chip pellets, to fire such heating systems. The Irish government has began a campaign to support renewable energy at the domestic level with grants for installing wood boilers, heat pumps, solar panels and

other renewable technologies. It is considered that these subsidies can improve the economic viability of bioenergy crops (Styles and Jones, 2007). *Miscanthus* can be burned in pellet or briquette form in domestic, community or industrial-sized boilers. In baled or shredded form it is better suited for combined heat and power (CHP) at an industrial level or in ground form for electric power in power stations. Studies generally agree that 1 t DM ha⁻¹ of *Miscanthus* contains 18 GJ of energy (Doyle, 2011) and Clifton Brown *et al.* (2004) predicted that, at its best, *Miscanthus* could substitute up to 37 % of Ireland's gross electricity generation. In addition, the production of electricity from *Miscanthus* is associated with a substantial reduction in GHG emissions (almost 90 %) when compared with conventional peat and coal electricity (Lewandowski *et al.*, 1995) and 93 % when compared with oil (Styles and Jones, 2008).

The recent increases in oil and gas prices, has dramatically increased the cost of electricity generation. This strongly influences the EU Emissions Trading Scheme (ETS) allowance prices. It is projected that ETS allowance prices will be buoyant and surpass the value necessary to make energy crop biomass economically viable on a power generation plant scale. ETS allowance prices would need to reach 16 euro t⁻¹ CO₂ for *Miscanthus* to become a competitive fuel (Styles and Jones, 2007). The rise in energy costs, coupled with competition from cheaper food imports has moved the balance in favour of producing energy crops over food crops. There are important factors to be considered before growing *Miscanthus*: a profitable end-user needs to be established due to the prohibitively high costs associated with the early stages of crop management (Table 1.3); the end-user should be located close to the site of production to reduce transportation costs and GHG emissions. Given Bord na Mona's power station locations and the presence of an internal railway network, suitable and cost-effective areas for *Miscanthus* co-firing plantations can easily be identified. Local production also has added social benefits for rural employment and development. Since *Miscanthus* is not a food crop, the land is also suitable for the spreading of waste products such as sewage sludge and farm effluents (Walsh, 1997), which may otherwise represent health risks if spread on food-producing ground. To achieve the targets set in the Energy White Paper the three power stations in Ireland must annually replace 900,000 t of peat with approximately 600,000 t of biomass from 2015. It is anticipated that the power stations will be capable of burning 4,000 ha of *Miscanthus* per station per year (Caslin *et al.*, 2010).

Table 1.3: The cost breakdown per hectare for the establishment and growth of *Miscanthus x giganteus* in Ireland (source Caslin *et al.*, 2010).

Activity	Cost Breakdown per Hectare
Number of rhizomes	150,000
Rotavating	€ 82
Harvesting	€ 850
Labour (5 men x 2 days)	€ 1100
Levelling	€36
Rolling	€21
Compensation to farmer (4yr land-use)	€3750
Transport	€300
Storage	€150
Total Cost	€6289

1.8: Site Description:

The experimental site was located within Oak Park Research Centre, Co. Carlow, Ireland, approximately 53°52’ N and 6°56’ W at an elevation of 56 - 60m above sea level (Figure 1.4). Oak Park is an Estate House set on extensive grounds, 2 km north of Carlow town. The Research Centre was established in 1961 as part of Teagasc (Ireland’s Agriculture and Food Development Authority) after the land was purchased by the Irish Land Commission. Oak Park is now the national centre for arable crop research with an emphasis on plant breeding, plant pathology, entomology and agricultural engineering. The land is divided into many different plots supporting a variety of research projects. Of the 340 hectares, over two thirds are arable. The soil is derived from limestone and falls into two categories; light textured gravelly soil and heavy textured clay soils. Plantations of Beech and Oak trees from 1700 can still be found in the Estate. There is also a 16-hectare artificial lake, which acts as a wildfowl sanctuary, providing shelter for many species of birds (Oak Park Research Centre booklet). In Oak Park the mean annual precipitation is 824 mm and mean annual temperature is 9.4 °C (Soussana *et al.*, 2007).

The *Miscanthus x giganteus* stand under investigation in this study was established in 1994. The stand was planted with rhizomes at a density of 11,000 rhizomes per hectare; after a year a second consignment of rhizomes was planted to fill in areas where the initial

plants had died. The stand is an unusual shape with a long narrower section abutting a wider rectangular area (see Figures 1.5 and 1.6). Adjacent to the stand is a small mature forest and a barley field. A small area of *Miscanthus sinensis* was also planted at the base of the stand as a productivity trail in early 2000. Although *M. giganteus* plants were dominant in the stand there was an understory canopy consisting of a variety of ruderal species (as described in chapter 2).

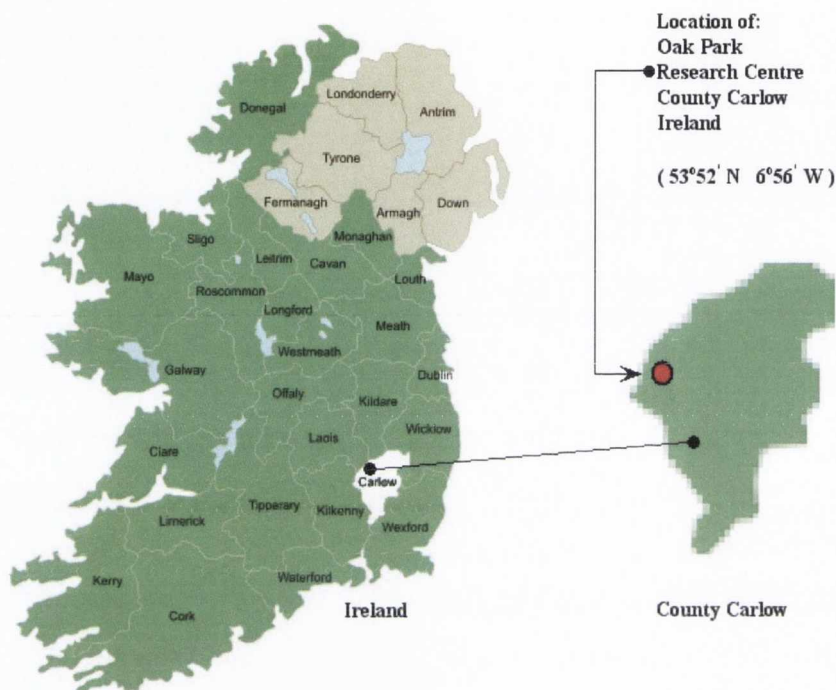


Figure 1.4: Map showing the location of County Carlow in Ireland and Oak Park Research Centre within County Carlow.



Figure 1.5: Photograph showing the positioning and shape of the *Miscanthus* stand in Oak Park Research Centre, Co. Carlow (taken from Google Earth)

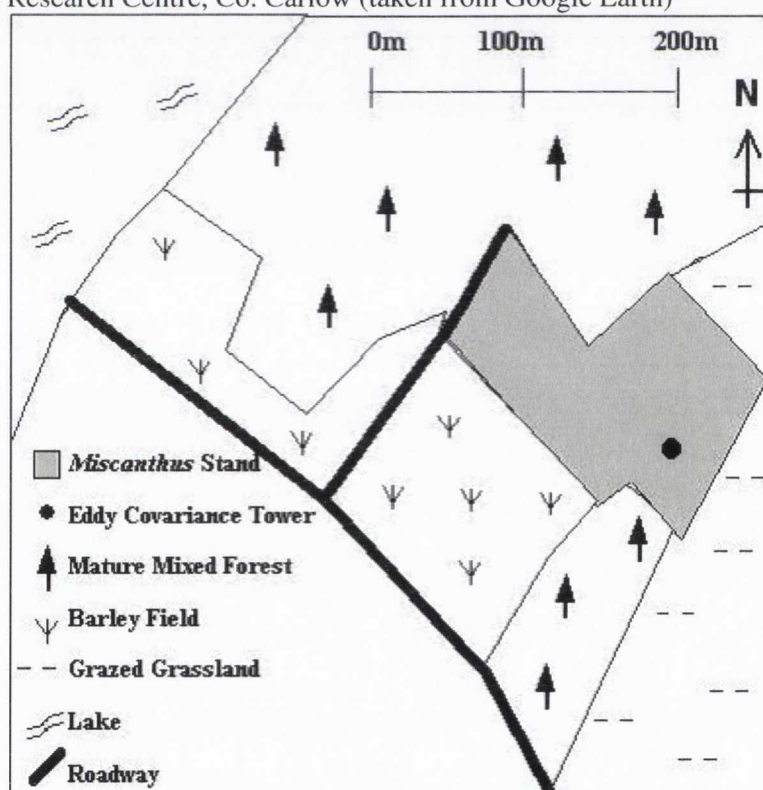


Figure 1.6: Line drawing showing the shape of the *Miscanthus* stand and the surrounding vegetation types in Oak Park Research Centre, Co. Carlow

1.9: Project Aims:

The primary aim of this project is to establish a carbon cycle for the energy crop *Miscanthus x giganteus* in Ireland. This will be achieved by:

- Quantifying the fluxes of CO₂ between the atmosphere and the *Miscanthus* ecosystem over two calendar years. This will be achieved through the eddy covariance technique (Chapter 3).
- Quantifying the fluxes of CO₂ from soil and plants within the *Miscanthus* stand. Soil respiration and leaf photosynthesis will be measured using the chamber method (Chapter 4).
- Quantifying the productivity of the *Miscanthus* crop over two growing seasons. Above and below ground biomass measurements will be made in conjunction with litter fall and decomposition measurements (Chapter 2).
- Quantifying the carbon sink or source strength of the *Miscanthus* ecosystem through utilising the results obtained; the information garnered will be used to investigate the potential of growing the bioenergy crop *Miscanthus* on Irish arable land as a means of contributing towards our national CO₂ abatement targets (Chapter 5).

Chapter 2

Above and Below Ground Biomass in a *Miscanthus x giganteus* Crop

2.1: Introduction:

The primary aim of this project is to establish a carbon cycle for the energy crop *Miscanthus x giganteus* in Ireland. This chapter specifically addresses the carbon in above and below ground biomass of the crop. The most obvious pool of carbon in the terrestrial biosphere is biomass. Carbon accumulates in living vegetation following photosynthesis; the quantity of biomass is a result of the difference between production through photosynthesis and consumption by respiratory and non-respiratory processes. The carbon held in biomass is important as it contributes to other pools; consumers, such as animals, bacteria and fungi, avail of this carbon as a source of energy for their own development. Determining biomass is a useful method of estimating the quantity of carbon in different plant components, as approximately 47 % of biomass is carbon (Harvey, 2007). Monitoring long-term changes in the biomass of different plant structures enable the identification of potential carbon sinks and sources and their variation over time. These data are useful in predictions of how carbon pools may change in the future and play an important role in completing carbon inventories. An assessment of biomass and carbon storage is of particular importance in relation to Article 3.4 of the Kyoto Protocol, where the potential mitigation of CO₂ emissions into biomass is detailed. Plant biomass refers to the weight of living plant material contained above and below a unit of ground surface area at a given point in time (Roberts *et al.*, 1985). The biomass of *Miscanthus* consists of stems, leaves, rhizomes, coarse and fine roots.

There is a relatively large body of data relating to above ground biomass measurements for *Miscanthus*; such data are essential when considering the viability of an energy crop (Beale and Long, 1995; Clifton-Brown *et al.*, 2000; Schwarz, 1993; Hotz 1996; Himken *et al.*, 1997; Venendaal *et al.*, 1997; Heaton *et al.*, 2009). Most field trials have been conducted on the *Miscanthus x giganteus* genotype (Hodkinson and Renvoize, 2001); this genotype has proven among the most productive (Clifton-Brown *et al.*, 2001). Harvested yields range from 5 to 55 t DM ha⁻¹ (Heaton *et al.*, 2010); however, most studies only cover 2-5 years of growth despite *Miscanthus* having a life cycle of 15-30 years. A productivity model (MiscanMod) was developed to predict potential *Miscanthus* yields for Ireland where water was not a limiting factor (Clifton-Brown *et al.*, 2001); MiscanMod was further developed to include Europe where potential yields ranged between 0 to 27 t DM

ha⁻¹ yr⁻¹, with yields greater than 15 t DM ha⁻¹ yr⁻¹ for more than 66% of ‘greater’ Europe, as defined by Hulme *et al.* (1995). In a further study extended to Eastern Europe and Northern and Central Asia, Fischer *et al.* (2005) used an agro-ecological zones (AEZ) methodology, to predict extremely high yields in Slovenia (27.5 t DM ha⁻¹ yr⁻¹) and Russia (28.1 t DM ha⁻¹ yr⁻¹). The modelled productivity for Ireland (using MiscanMod) ranged from between 16 to 26 t DM ha⁻¹ yr⁻¹ (Clifton-Brown *et al.*, 2000), while harvested yields at the Oak Park site averaged approximately 8.8 t DM ha⁻¹ yr⁻¹ (Table 2.1). MiscanMod predicts autumn harvest yields, prior to significant leaf senescence; therefore, the estimates are not the yields a farmer could expect. In Ireland a rate loss of 0.3% of dry weight per day delay in harvest has been recorded (Clifton-Brown *et al.*, 2001). Harvesting in early spring allows for assimilate translocation to the roots and rhizomes (Hayashi *et al.*, 1981; Long *et al.*, 1989; Greef and Deuter, 1993).

Table 2.1: Dry matter yields of *Miscanthus x giganteus* per hectare made in Springtime (Late March to Mid April) from the *Miscanthus* stand in Oak Park Research Centre, Co. Carlow. * denotes agricultural yields (yields do not include harvest losses or senesced material on the ground), ** denotes biological yields (yields include harvest losses but not senesced material on the ground). Data provided by Dr John Finnan, Research Officer in Oak park Research Centre (pers. comm., 2011).

Year	Yield (t DM ha ⁻¹)
2003	9.15*
2004	5.15*
2005	No data available
2006	No data available
2007	10.12**
2008	10.15**
2009	7.14**
2010	10.15**
2011	10.17**

The high biomass yields from *Miscanthus* have been attributed to its high efficiency of light interception, high photosynthetic capacity and high conversion to dry matter (Naidu *et al.*, 2003; Long, 1999; Beale *et al.*, 1996; Beale and Long 1995). *Miscanthus* has the C4 photosynthetic pathway, which is considered to be the greatest efficiency and potential productivity of all forms of higher plant photosynthesis as it largely eliminates the competing photorespiration (Long, 1999). Radiation use efficiencies of C4 species can be considerably greater than those of C3 species; consequently, their annual biomass production is greater (Squire, 1990). In contrast to many other C4 species *Miscanthus* can achieve and maintain high CO₂ assimilation rates under cool conditions (Naidu and Long 2004; Farage *et al.*, 2006). Numata (1979) suggests this is due to *Miscanthus* naturally

occurring and adapting to cooler climates. In fact *Miscanthus* has greater radiation-use-efficiency than other C4 crop in cool to temperate climate conditions (van der Werf *et al.*, 1993). Low temperatures can influence leaf photosynthesis through reducing the efficiencies of the existing leaves and influencing the efficiency of new leaves once they mature (Beale *et al.*, 1996) by reducing the activity of stromal enzymes and thylakoid proteins (Stamp, 1987). The maintenance of protein and enzyme contents in leaves of *Miscanthus* grown at low temperatures may be critical to its ability to realise high photosynthesis at sub-optimal temperatures (Kubien and Sage, 2009). *Miscanthus* growth can be limited by water supply and irrigation is required to produce commercially viable yields in some parts of Central Europe. In lab conditions Clifton-Brown and Lewandowski (2000) found a linear relationship between water added and biomass produced in *Miscanthus* plants grown at different levels of water supply. Clifton-Brown *et al.* (2002) reported that *Miscanthus* does not have a flexible water saving strategy. In contrast, Foti *et al.* (2003) have observed a decrease in leaf transpiration and stomatal conductance at low soil water conditions. This decrease in stomatal apertures did not immediately affect leaf net photosynthesis. There is a debate in the literature about the effect of nitrogen fertilization on *Miscanthus* crop yields (Ercoli *et al.*, 1999; Himken *et al.*, 1997; Christian *et al.*, 1997; Schwarz *et al.*, 1994). Generally, the C4 photosynthetic pathway allows plants to have higher efficiencies of nitrogen and water-use (Ehleringer and Monson, 1993).

Below-ground biomass is often neglected in biomass studies. This can be a substantial omission, particularly for perennial crops with extensive root and rhizome systems. The mass, size and distribution of root and rhizome biomass is central in carbon cycling, as it forms a major carbon pool in the soil. It has been shown that *Miscanthus* roots and plant residue in the soil can commonly contribute up to 2.75 t DM ha⁻¹ yr⁻¹ (Harwood *et al.*, 1998). It is generally more difficult to measure below ground biomass compared to above ground, regardless, it is important to attempt to measure both to allow investigations as to whether changes in above ground productivity results from photosynthetic gains or from a redistribution of carbohydrate resources from the root system (Roberts *et al.*, 1985).

In the literature there remains a strong debate as to the best methodology for determining root biomass and production (Vogt *et al.*, 1998). Regular coring or the use of in-growth cores are the most commonly employed techniques. In-growth cores can cause considerable disturbance to the soil and associated micro-climate, which could greatly influence root growth rates; disturbance effects include soil compaction, penetration

resistance, water retention and altered nutrient concentrations (Trujillo *et al.*, 2006). The in-growth method was therefore deemed inappropriate for the *Miscanthus* site; in addition, within the time frame of the experiment the in-growth cores would only assess fine root growth, neglecting the contribution of coarse roots and rhizomes to the below ground biomass. Instead, sequential coring was deemed the best possible and practical technique for tracking developments in the rooting system over a growing season at the *Miscanthus* site. Regular coring over an entire growing season is important as root turnover can vary significantly between seasons (Trujillo *et al.*, 2006). Despite the relatively crude methodology, coring allows for sampling of large areas and it also enables sampling of rhizome, coarse and fine roots.

2.1.1: Litter Fall and Litter Decomposition:

Plant detritus is a major component of ecosystems providing food, a reservoir of nutrients and regulating hydrology (Sing and Gupta, 1977). The input of organic matter to the soil is an important factor in carbon cycling; it is essential to quantify its input and its rate of decomposition. To assess the amount of mobilised carbon, measurements of litter fall, litter decomposition and root turnover are required. Roots provide a path for the movement of carbon from plants into the soil and so root production and turnover directly impact on the carbon cycle in an ecosystem (Matamala *et al.*, 2003). Nevertheless, accurate estimations of turnover rates are difficult to obtain. Root turnover measurements usually rely on pulse-labelling experiments using ^{14}C or ^{15}N -enriched fertilisers, or the installation of a glass wall to monitor changes in the rooting system. The addition of fertilisers or a glass wall can dramatically alter the natural rooting environment and so cannot be relied upon to yield data that represents the true root turnover rate. The use of the isotopic composition of CO_2 added to air in elevated CO_2 experiments is also often employed to quantify the turnover of carbon in roots. As this study is based on carbon fluxes in ambient field conditions the enrichment of the environment with CO_2 was not considered acceptable. For these reasons no root turnover experiments were conducted; only litter fall and litter decomposition were measured.

Decomposition is the process of converting dead organic matter into smaller, simpler compounds. The decomposition of leaf litter is a complex process and varies depending on the substrate and the environment. Generally, decomposition increases with temperature, although leaf decomposition has been shown to occur at low levels even under deep snow (Taylor and Jones, 1990). The influence of moisture on decomposition is more complex

with waterlogged and very dry conditions reducing biological activity and therefore decomposition rates; intermediate water conditions lead to highest rates of decomposition. The attractiveness of the litter as a food source for decomposers is a further important factor, varying among species (Adams and Angradi, 1996) and over time (McClaugherty and Berg, 1987). Generally, high quality, nutrient-rich leaves with a high C:N ratio decompose faster than low quality leaves.

Litter decomposition is most commonly measured using the litter-bag technique (Wieder and Lang, 1982). A known quantity of litter is placed in a mesh bag and then inserted into the litter layer, thus being exposed to the normal fluctuations in temperature and moisture. Bags are harvested periodically, dried and reweighed to determine the amount of mass lost over time. Enclosing litter in perforated bags and monitoring decomposition is a long-established technique (Falconer *et al.*, 1993; Johnston, 1935; Lunt 1935). Litter-bags were first described in the literature by Shanks and Olson (1961). The technique assumes that the material in the bag is representative of the dead material present at the time of installation and that placement in bags does not affect natural decomposition rates (Roberts *et al.*, 1985). Critics of the technique, including Kurz-Besson *et al.* (2005) and Kurz *et al.* (2000), argue that the presence of bagging materials can significantly alter the micro-environment surrounding the litter, usually leading to an underestimation of rates. Litter-bags can cause leaf compaction, impede air movement, alter natural evaporation rates and the mesh size can exclude micro-invertebrates (Stewart and Davies, 1989). In addition, oven-drying the litter prior to placing it in the bag, which is essential to establish its original dry weight, could alter the lability of the litter and viability of its associated microbial population.

2.1.2: Vegetation Surveys:

When investigating the carbon cycle of an energy crop it is essential to study the ecosystem in which it is grown. Monitoring the establishment and development of additional plant species is vital as these plants could be a significant sink or source of carbon over the study period. In addition, they may compete with the energy crop for resources and potentially reduce crop productivity and yield.

In a *Miscanthus* stand a variety of ecological niches exist (Oliveira, 2001) due to low planting densities, the relatively large spaces between individual plants and the change in canopy closure over the growing season. Opportunistic species can take advantage of gaps

within the canopy. Once the full canopy develops, the germination of new weed species is dramatically reduced as light levels penetrating into the under-storey decline. Only shade-tolerant or very mature species survive, they usually become etiolated and offer little competition to the *Miscanthus* crop (Christian and Haase, 2001). Most weeds establish after the *Miscanthus* has been harvested due to increased light levels and soil disturbances, which promote seed germination. The development and diversity of under-storey species is affected by the site location, the climate and, most importantly, the previous land use (Christian and Haase, 2001).

2.1.3: Aims:

The aim of making biometric measurements on the *Miscanthus* stand is to provide productivity data, which offers important insights into the growing patterns of an older *Miscanthus* stand compared to younger crops reported in the literature (Heaton *et al.*, 2010). In addition, biomass estimates are needed to complete a carbon inventory for the *Miscanthus* crop; showing the assimilation and changes of carbon in different organs over a growing season. Recording litter fall and litter decomposition permits an assessment of the input of organic matter into the ecosystem, while vegetation surveys provide information regarding the composition of the *Miscanthus* stand. A further aim was to produce a simple model that can be used in the field to relate standing biomass to dry weight yields. The goal is to provide Irish farmers with an estimate of crop yields without having to perform destructive harvests.

2.2: Methodology:

2.2.1: Measuring *Miscanthus* Biomass:

Assessments of *Miscanthus* biomass and productivity were made over the study period as follows:

(1) A preliminary biomass assessment was conducted in November 2005, where the above and belowground biomass of two quadrats (1m²) were determined. Previous studies have suggested that root biomass is at a maximum in the month of November (Neukirchen *et al.*, 1999; Beale and Long, 1997). The total number of *Miscanthus* plants and the average height of the shoots present were measured and calculated. The fresh and dry weight of all leaf and stem material was determined. A complete root excavation was performed, until no root material remained visible in the soil. Soil must be dispersed for the successful separation of the roots; therefore, soil samples were soaked in soapy water to loosen the

soil from the root biomass. The water was then agitated and most of the rhizomes and roots floated and were picked out and placed in a beaker of water. The liquid part of the soil mixture was poured slowly through a plastic sieve; root material collected here was transferred into the beaker of water. The remaining soil solution was passed through a metal sieve (0.2 mm mesh size), and washed with a squirt bottle. There is no agreed standard size of mesh used during root washing (Gregory, 2006; Amato and Pardo, 1994); but mesh sizes < 0.5 mm have been proven adequate in other trials (Livesley *et al.*, 1999). Forceps were used to sift through the sample and any remaining roots were removed. The rooting system was divided into rhizomes, coarse roots and fine roots based on diameter sizes: coarse roots with a diameter > 2 mm, fine roots < 2 mm. The rhizomes and roots were dried at 80°C until they reached a constant weight.

(2) A non-destructive 'biomass tracking experiment', was established in July 2006. One hundred *Miscanthus* plants, chosen at random, were labelled. The stem height, stem diameter and the total number of leaves present on each plant were measured on the 31st July, 24th August, 3rd October and 14th December. This procedure was adapted from a study measuring NPP in perennial salt marsh plants in Essex described by Hussey and Long (1982). *Miscanthus* stems are elliptical (Kaack and Schwarz, 2001); stem diameter measurements were made on the greater of the two diameter axes.

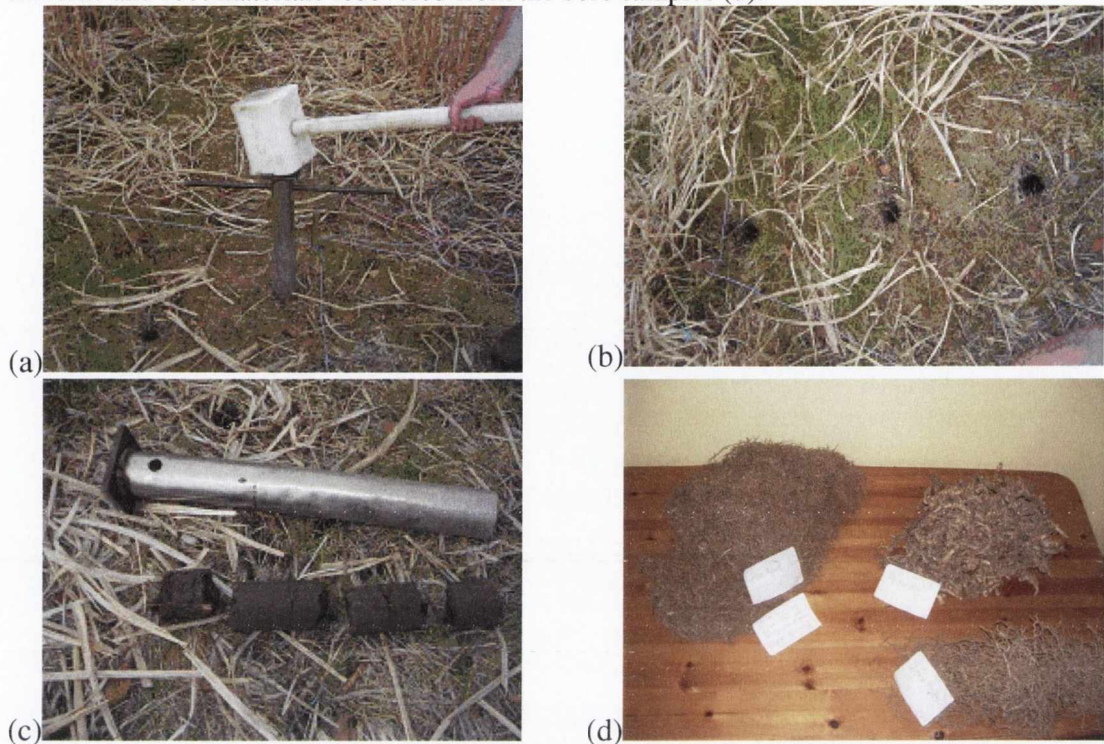
(3) To complement the 'biomass tracking experiment' a destructive sampling campaign was started on 3rd August 2006 and ran for 21 weeks until 23rd December 2006. During this period, 10 *Miscanthus* plants were harvested randomly every week. Stem height, stem diameter, the number of leaves present, total leaf area and fresh and dry weights of stem and leaf material were measured.

(4) For the 2007/2008 campaign a combined above and belowground biomass sampling programme was carried out. A 53 m^2 area of *Miscanthus* plantation was sectioned off in June 2007 following shoot emergence. 64 permanent quadrats (1 m^2) were established in an 8 by 8 formation with 5 m between each quadrat in every direction. A buffer zone, at least twice the maximum canopy height, is recommended when carrying out destructive harvesting so as not to affect any adjacent quadrats through increased light penetration (Roberts *et al.*, 1985). Six randomly chosen quadrats were harvested each month from July 2007 to April 2008. For the above ground biomass the following measurements were made: stem height, stem diameter, number of leaves present, dry weights of stem and leaf

material and estimates of the LAI (leaf area index) for each quadrat were derived using a SunScan probe (Delta-T Devices Ltd., Cambridge, U.K.). Above ground harvested material was placed in labelled plastic bags along with a small quantity of water to reduce desiccation damage and sealed. The samples were stored between 2-5 °C and all consequent measurements were carried out within 24 hours of harvesting. For below ground biomass assessment, three cores, 30 cm in depth and 10 cm in diameter, were extracted from each quadrat (18 cores per month) and the dry weights of the rhizome, coarse and fine roots components were determined. The coring technique removed 2.35% of the soil volume in each 1 m² quadrat. To avoid a selective bias all cores were taken at defined sampling points, one at the centre of each quadrat, one at the top left hand corner and one at the bottom right hand corner (Plate 2.1). To avoid root decomposition, soil cores were stored at 4 °C and roots were washed out within 7 days of extraction as described above.

It is important to note that no distinction between living and dead material was made so measurements were made on plant material and not strictly biomass (which is only living matter). There are three main techniques employed to distinguish between living and dead root material: colour differences, floatation methods, and vital staining. All three techniques have strong drawbacks. Firstly, using colour to distinguish between living and dead material is highly subjective. Secondly, floatation depends on the living roots floating and the dead roots sinking; the technique is species specific, in some cases all root types sink (Roberts *et al.*, 1985). Finally, the vital staining method is based on the principle that living roots absorb certain stains while dead roots remain unstained. However, it has been found that micro-organisms on the root surface are capable of absorbing the stain giving dead roots the appearance of living ones. In addition, in dark roots the stain is not always visible. Due to the difficulties involved in reliably separating living and dead material (Hussey and Long, 1982) no distinction was made here and instead the dry weight of the entire underground plant material was calculated.

Plate 2.1: Coring in the *Miscanthus* stand (a), showing the location of the sampling sites within a quadrat (b), an example of an extracted soil core (c), and an example of the dried rhizome and root materials recovered from the core samples (d).



2.2.2: Measuring Litter Fall in the *Miscanthus* Stand:

Different techniques were used to measure litter fall in the 2006/2007 and the 2007/2008 seasons. In the first season, eight plastic boxes (100 x 50 x 50 cm) were installed at random locations in the *Miscanthus* stand. The boxes acted as litter traps, gathering falling leaf litter. The boxes were visited weekly and any litter present was collected and dried at 80 °C to a constant weight. The litter trap experiment was continued in the following growing season but the design was changed to avoid omitting some litter fall through size exclusion. In April 2007, six flat litter trap quadrats (1 m²) were installed; the base of the quadrat consisted of black sacking material, cut around *Miscanthus* stems, so as not to impede growth. Any litter gathered on the black sacks was collected. The traps remained in position until harvesting in March 2008. The traps were visited weekly.

2.2.3: Measuring Litter Decomposition in the *Miscanthus* Stand:

A 'litter-bag' experiment was established to measure litter decomposition rates. Twenty-four litter-bags were constructed out of 'chicken wire' fencing material with a mesh size of 19 x 25 mm. The litter-bags measured 100 x 25 cm; this size was chosen to accommodate the large *Miscanthus* leaves, while preventing compaction and litter loss through fragmentation. The litter-bags were filled with 50.0 g of plant material that had been dried at 30 °C and labelled with coloured cable ties for identification. Three bags were assigned as controlled samples; they were brought into the field and returned immediately to the lab. The bags were re-weighed to investigate the proportion of detritus material lost in handling and this was then used to eliminate the systematic error associated with loss during travel. In addition, a subsample of the control material was also dried at 105 °C to determine if a 30 °C–105 °C temperature conversion factor was required. The remaining twenty-one litter-bags were installed in the *Miscanthus* stand in early March 2008. Leaf litter on the ground surface was collected and set aside. The litter-bags were installed in three rows of seven bags each two meters apart. The bags were secured to the soil surface using tent pegs, the set aside leaf litter was re-dispersed over the experimental site (Plate 2.2). This simulated the normal conditions in the field and allowed the samples be incubated *in situ*. Three litter-bags, one from each row, were retrieved from the site every month. Any fresh biomass, such as grass seedlings, was removed. The leaf litter was then dried at 105 °C to a constant weight. The percentage mass loss and remaining biomass were calculated.

Plate 2.2.1: The litter trap experiment: The area was cleared of litter



Plate 2.2.2: The litter-bag was placed in the clearing and secured with pegs



Plate 2.2.3: The leaf litter was re-dispersed over the litter-bag



2.2.4: Vegetation Surveys:

A practical and direct technique to monitoring under-storey species development is through repeated vegetation surveys. The Braun-Blanquet (1932) scale is a technique that provides plant population information that stresses the value of cover as an indication of the relative importance of various species within a community. In August 2006, two transects (170 m) were established bisecting the *Miscanthus* stand. Temporary quadrats (1 m²) were placed every 10 metres along the two transects. A total of 33 quadrats were examined. When a species could not be identified in the field, a specimen was brought back to the lab where reference books or experts were consulted. The percentage cover of each layer of vegetation was noted; the percentage cover was assumed to be an estimation of the space covered by a vertical projection of all above ground plant parts. Each species was given a cover-abundance index using the following scale (Braun-Blanquet, 1932):

- 5 Covers more than 75% of the area
- 4 Any number of individuals covering 50-75% of the area
- 3 Any number of individuals covering 25-50% of the area
- 2 Very numerous, or covering at least 5% of the area
- 1 Plentiful but small cover value
- + Sparsely or very sparsely present, cover very small
- R One individual present.

All the under-storey species present in each quadrat were recorded (Appendix 1). In March 2007 the study was repeated (Appendix 2). The two surveys provided information on the vegetative composition in the *Miscanthus* stand at maximum canopy closure, in August, and complete canopy openness, in March. In May 2007, 10 permanent quadrats (1 m²) were set up within the *Miscanthus* stand. The quadrats were revisited on ten occasions, between May 2007 and July 2008, to track changes in under-storey vegetation over the growing season (Appendices 3 to 12).

2.3: Results:

2.3.1: (1) Preliminary Biomass Assessment: 2005:

2.3.1.1: Above Ground Biomass:

To estimate above ground biomass two 1m² quadrats were harvested in November 2005. The average height of the shoots was 2.32 m (n = 130) and the total above ground biomass yield was 19.54 t DM ha⁻¹. Stems contributed 14.93 t DM ha⁻¹ and leaves the remaining 4.61 t DM ha⁻¹.

2.3.1.2: Below Ground Biomass: Excavation Technique:

A preliminary assessment of the rooting depth of *Miscanthus* at the Oak Park site was made in November 2005 using the method of complete soil excavation. 97 % of the rooting system was found between 0-30 cm (18.28 t DM ha⁻¹) and the remaining 3 % (0.56 t DM ha⁻¹) was located between 30-60 cm. No roots were found below 60 cm. Figure 2.1 shows the contribution of fine and coarse roots and rhizomes at the 0-30 cm and 30-60 cm soil depth ranges. As expected the majority of rhizomes were located in the upper 30 cm of soil, although they still accounted for 20 % of rooting material between 30-60 cm; rhizomes accounted for 78 % of the rooting system in the upper portions of soil. Fine roots contribute to almost half (48 %) of the below ground biomass in the 30-60 cm soil depth range; although at the experimental site very little root material was found at this depth range.

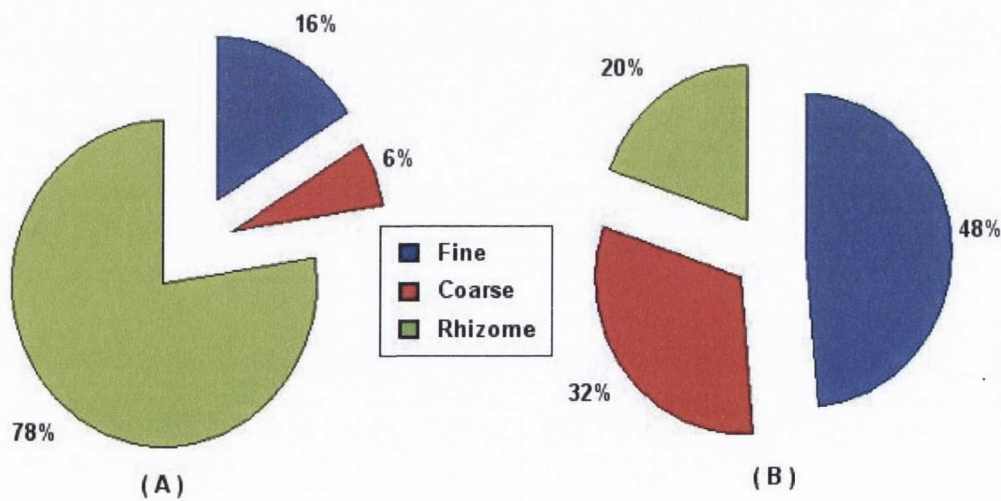


Figure 2.1: The relative contributions of rhizomes, coarse and fine roots and at the 0-30 cm (A) and 30-60 cm (B) soil depth ranges. Measurements performed in November 2005 on the *Miscanthus* stand in Oak Park Research Centre, Co. Carlow from two 1 m² quadrats.

2.3.2: (2) Non-destructive Biomass Tracking:

2.3.2.1: Stem Height:

To ensure the 100 plants chosen to represent the *Miscanthus* stand in the ‘tracking experiment’ displayed a normal distribution, frequency histograms were plotted for stem height, diameter and leaf number for each measurement period (31st July, 24th August, 3rd October and 14th December) (Figures 2.2-2.4) using bin averages using the computer programme Origin 5.5. Standard Gaussian curves were seen for the stem diameter and leaf count data (Figures 2.5 and 2.6). The stem height data did not display the Gaussian form and instead, two distinct populations were identifiable at each measurement period (Figure 2.7).

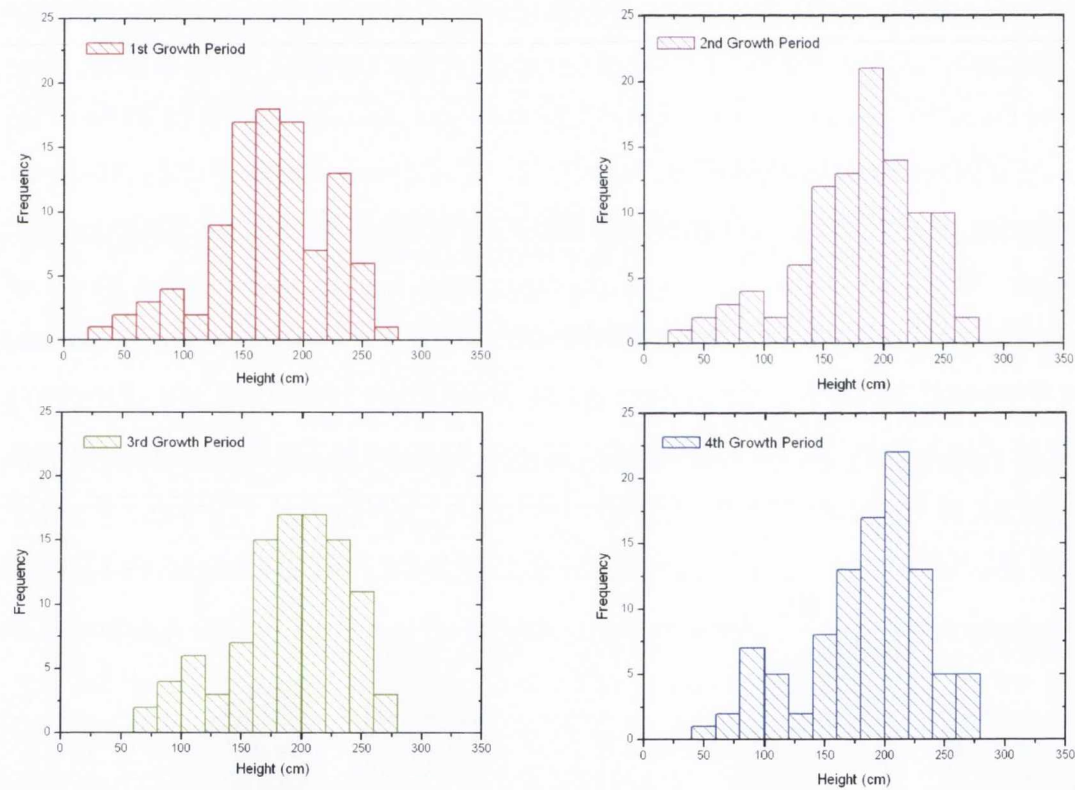


Figure 2.2: Population frequency histograms for stem height for the four measurement periods (31st July, 24th August, 3rd October and 14th December 2007).

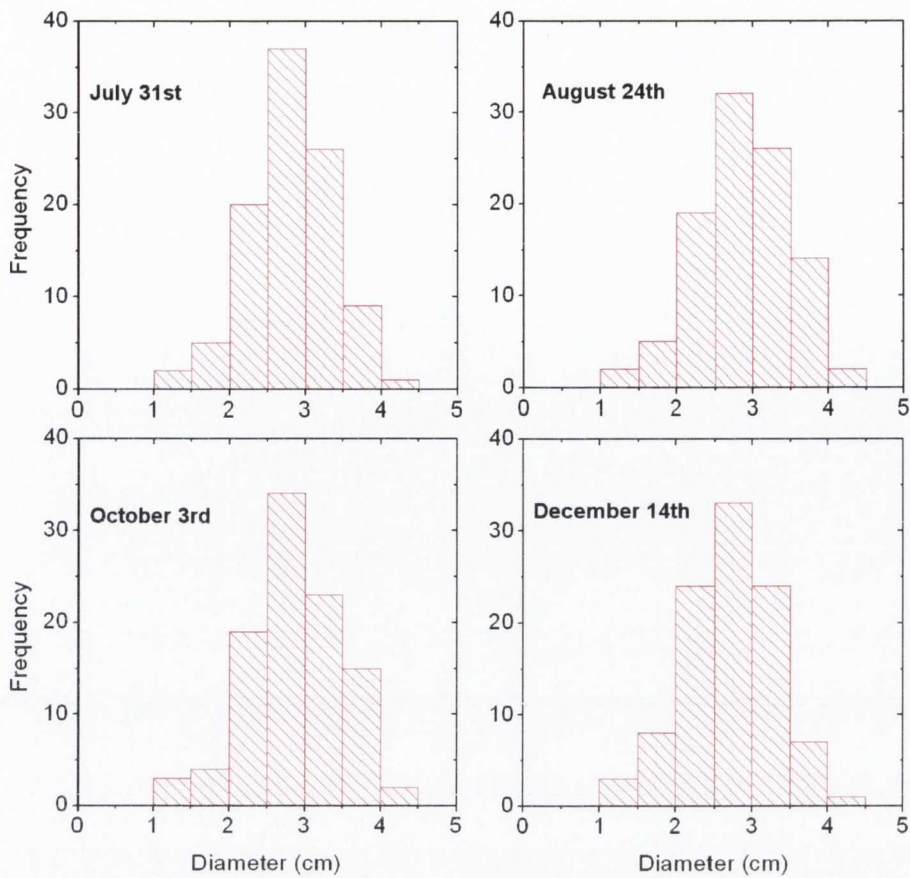


Figure 2.3: Population frequency histograms for stem diameter for the four measurement periods (31st July, 24th August, 3rd October and 14th December 2007).

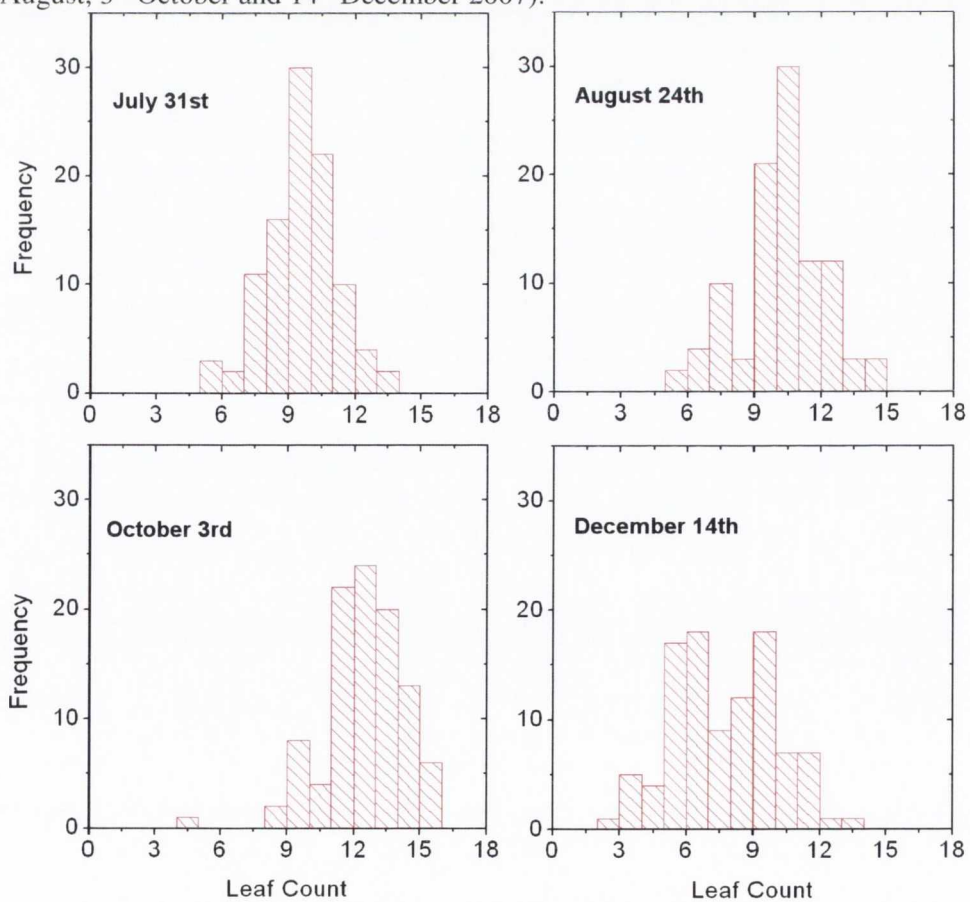


Figure 2.4: Population frequency histograms for leaf number per stem for the four measurement periods (31st July, 24th August, 3rd October and 14th December 2007).

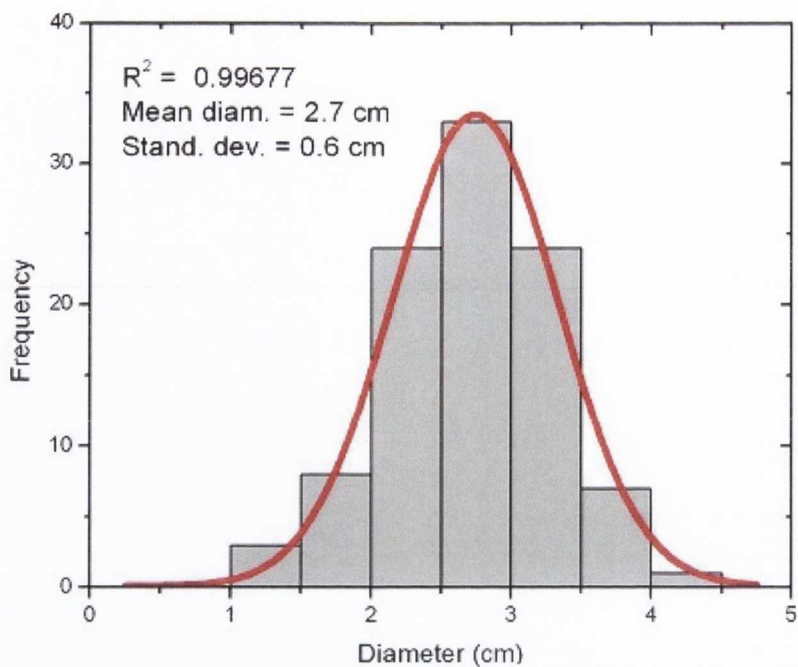


Figure 2.5: *Miscanthus* stem diameter data showing normal population distribution from July 31st to December 14th 2007.

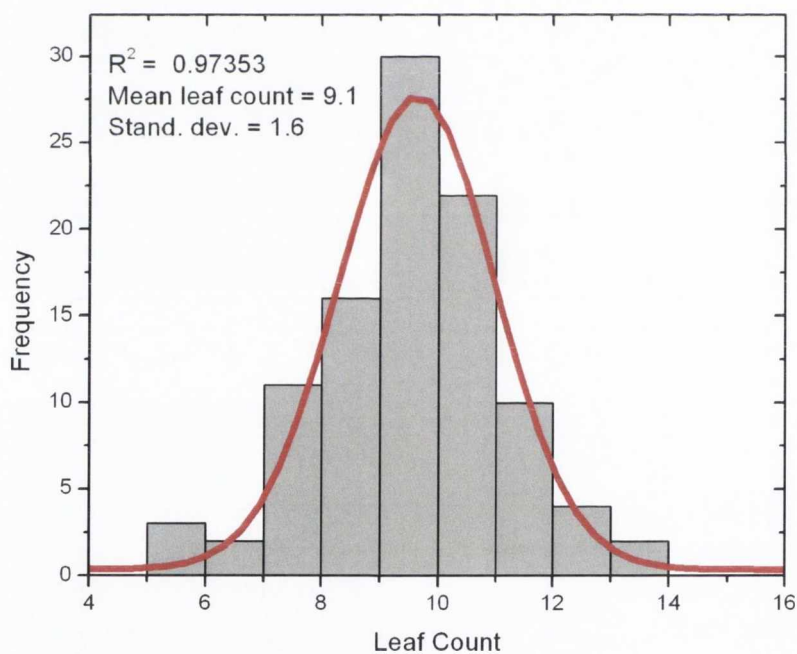


Figure 2.6: *Miscanthus* leaf number data showing normal population distribution from July 31st to December 14th 2007.

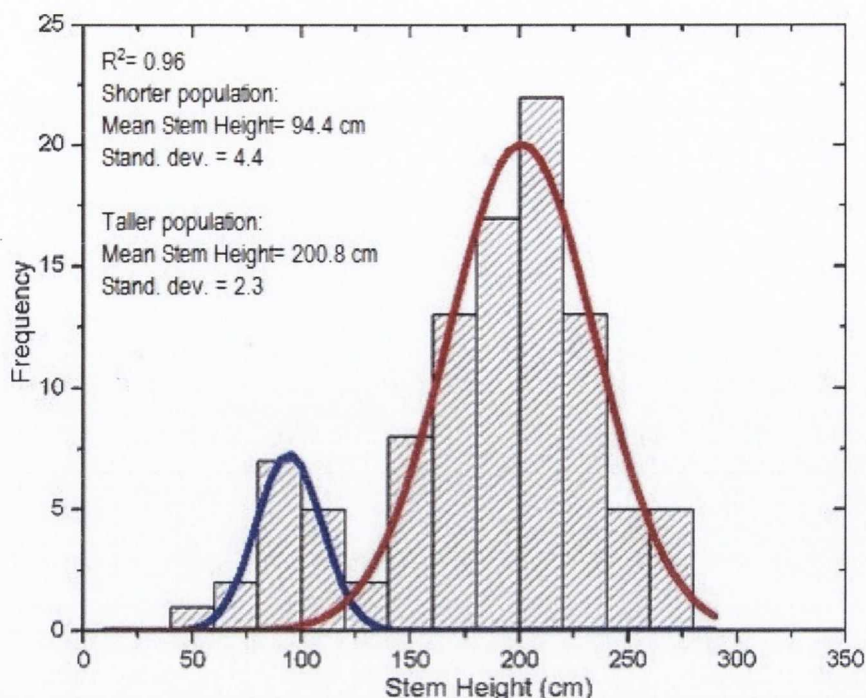


Figure 2.7: *Miscanthus* stem height data showing two distinct populations, both with normal distribution from July 31st to December 14th 2007. 14 % of the samples fell within the shorter population (blue) while the taller population (red) accounted for 86 % of the samples.

Treating the stem height data as a single population would disregard the evidence that the data were not normally distributed. Therefore, the data set was divided into 'shorter' and 'taller' groups. The distinction was made for each measurement period based on frequency distribution graphs. Figure 2.8 shows the change in stem height for the two groups over the experimental period. On average there was a 1.07 m difference in height between the two groups at each measurement time. Both groups followed the same trend with an increase in stem height until the October 3rd measurement period and thereafter decreased to a similar height as at the beginning of the experiment. 90 % of the *Miscanthus* plants demonstrated an increase in stem height over the first three measurement periods. A mean stem growth of 17 cm was seen between the beginning of the experiment (July 31st) and the third measurement (October 3rd) corresponding to an average growth rate of 0.27 cm day⁻¹. An unexpected result was discovered when comparing the changes in stem height between the third (3rd October) and fourth (14th December) measurement intervals. It was assumed that most stems would exhibit a drop in stem height due to senescence, however, 43% of the data showed an increase in stem height over this period. Furthermore, this phenomenon was seen equally in both the 'shorter' and 'taller' populations. Figure 2.9 displays the change in stem height for 10 randomly chosen plants, half of which show senescence and the other half show growth. In fact, the 'shorter' population showed a rapid increase in stem growth during this period.

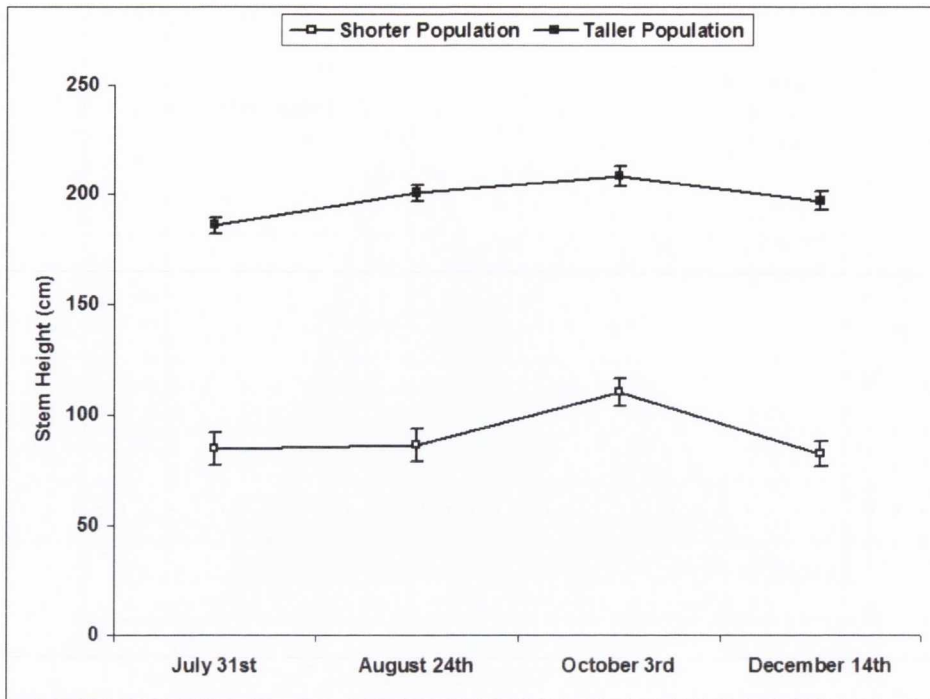


Figure 2.8: Mean stem height (cm) for the ‘shorter’ and ‘taller’ *Miscanthus* groups over the experimental period. Error bars are $\pm$ standard error

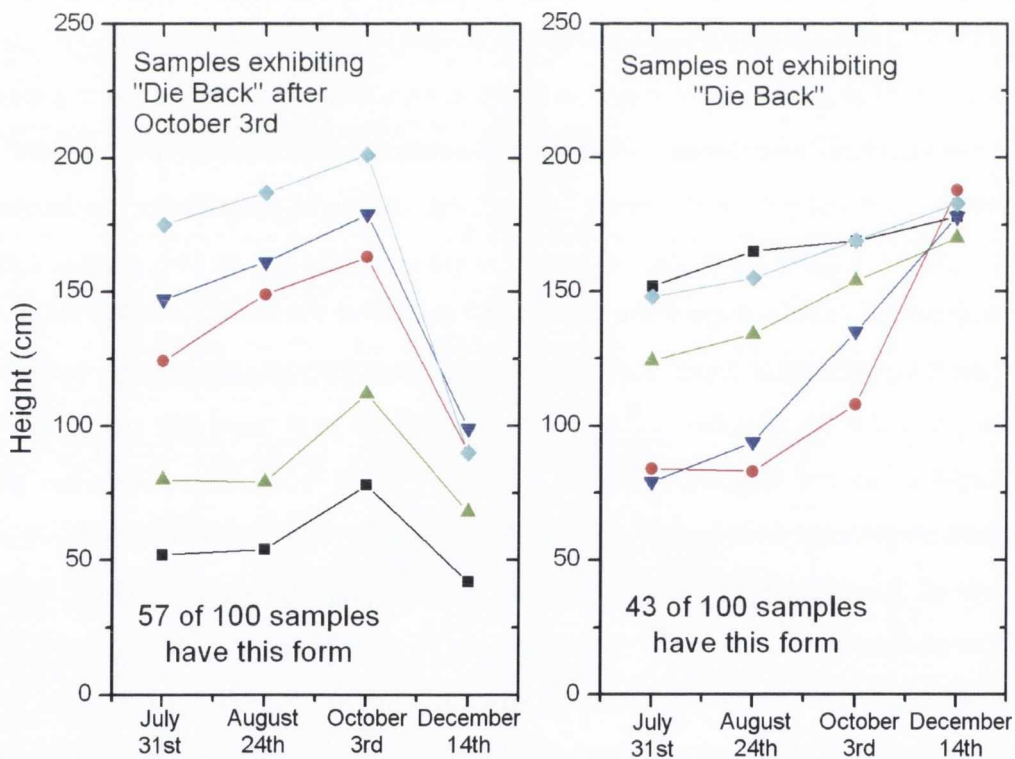


Figure 2.9: Change in stem height for 10 randomly chosen plants over the experimental period. 57% of stems decreased in height after October 3rd; 43% of stems increased in height after this date.

2.3.2.2: Stem Diameter:

The stem diameter data exhibited a normal distribution for all periods and so were analysed as a single population. Figure 2.10 shows the mean change in stem diameter over the experimental period. On average, stem diameters increased from measurement period 1 (2.77 ± 0.54) to period 2 (2.81 ± 0.60), followed by a slight decrease in period 3 (2.81 ± 0.61) and a more substantial decrease to minimum values in period 4 (2.64 ± 0.58). Upon further investigation, three distinct changes in diameter size were seen within the *Miscanthus* population (Figure 2.11). Approximately, 65 % of the samples showed very little change in stem diameter over the experimental period. 25 % of the stems demonstrated a considerable decrease in diameter, between the third and fourth measurements. The decrease was substantially greater than the overall average would suggest. Finally, 10% of the population displayed a growth in stem diameter between the last two measurement intervals in October and December.

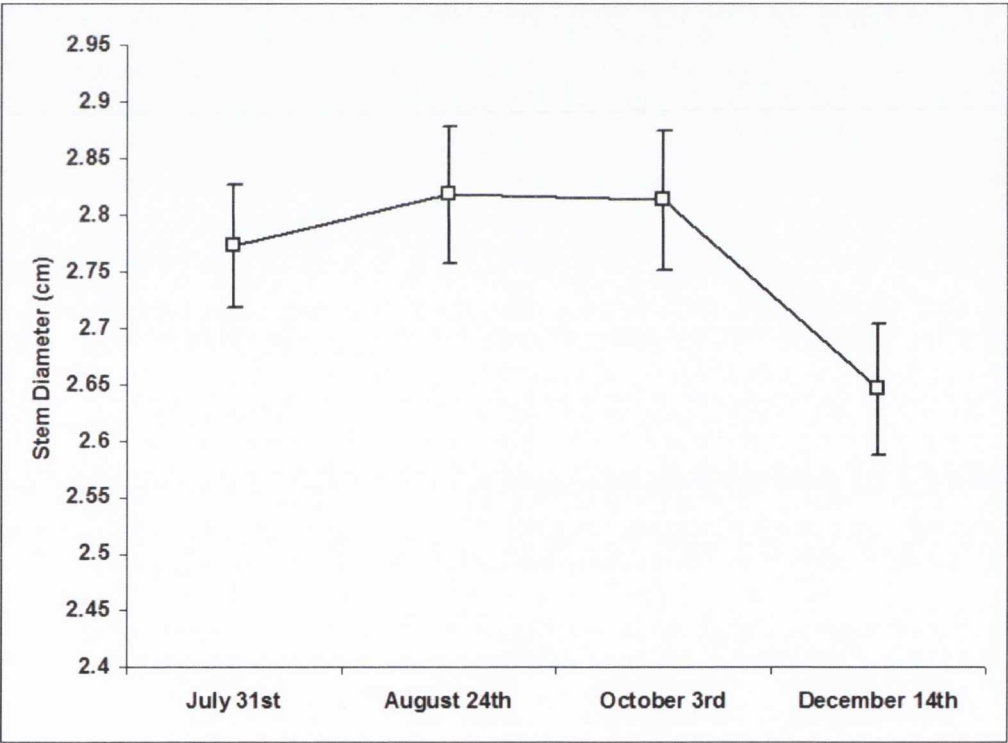


Figure 2.10: Mean stem diameter of *Miscanthus* stems (n=100) over the experimental period. Error bars are $\pm$ standard error.

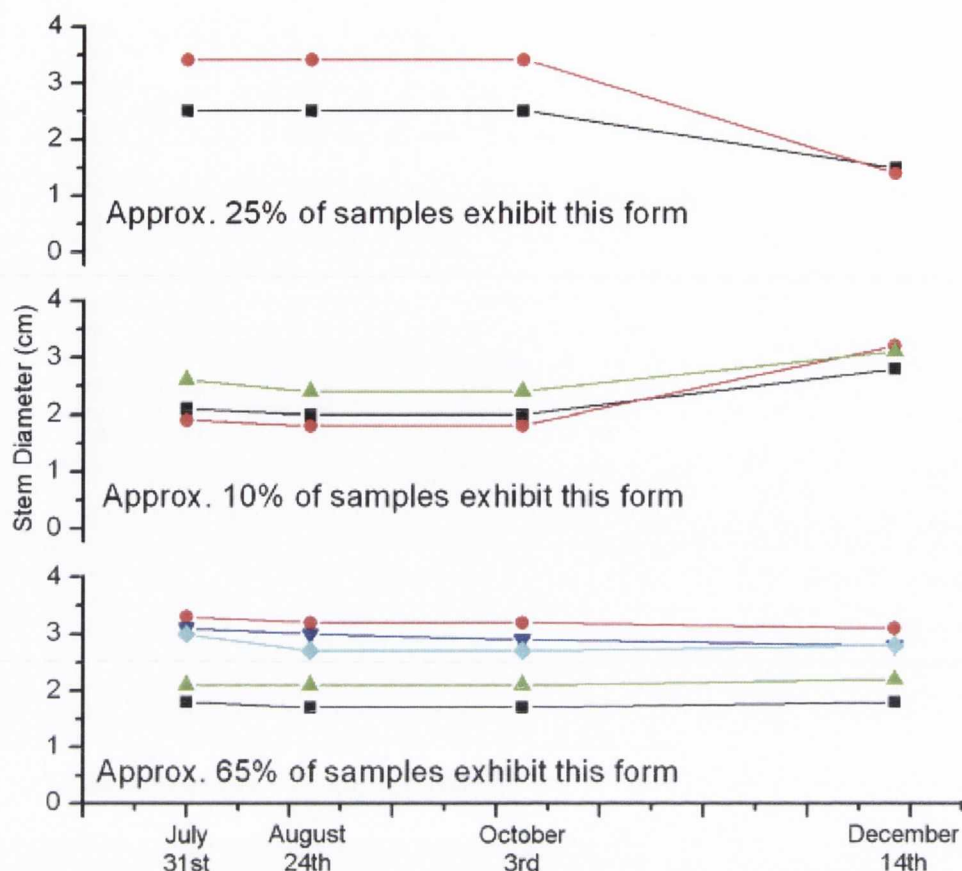


Figure 2.11: Three distinct patterns of changes in stem diameter over the experimental period.

2.3.2.3: Leaf Count:

The number of leaves present per stem displayed a normal distribution. The frequency histograms showed a gradual shift towards higher leaf numbers over the first three measurement intervals; the samples display greater variation in the final period due to senescence. The mean leaf count per stem is shown in Figure 2.12. 95 % of the samples showed an increase in leaf numbers between measurement periods 1 and 3 and a reduction in period 4. The peak in leaf numbers, were recorded during the October 3rd measurements with an average leaf number of 11.94 ± 1.8 .

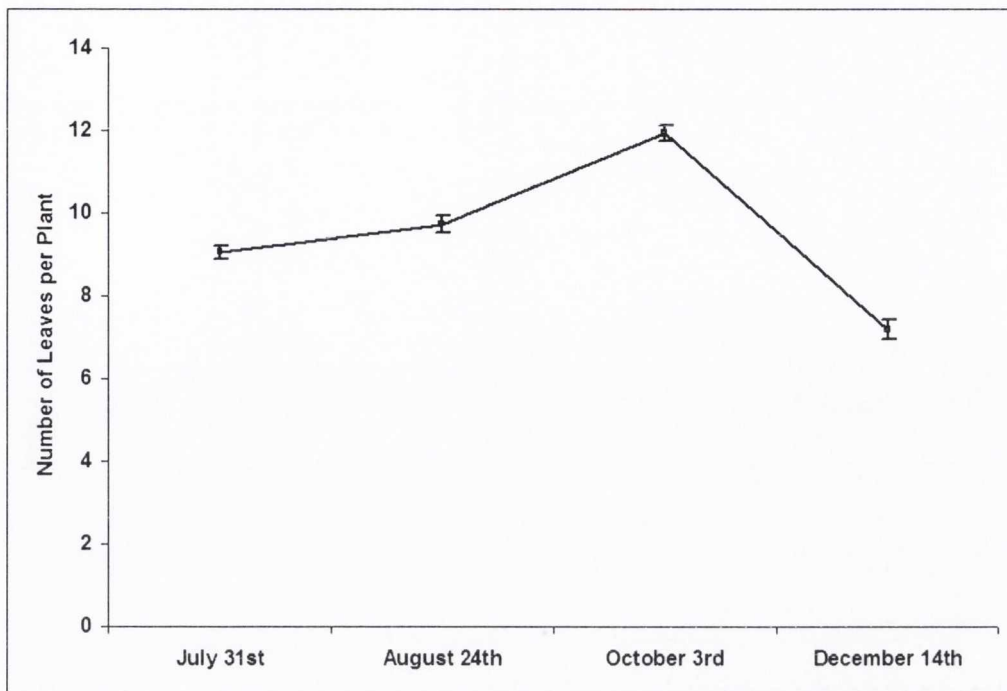


Figure 2.12: Number of leaves present per *Miscanthus* stem (n=100) over the experimental period. Error bars are $\pm$ standard error.

2.3.3: (3) Destructive Sampling: 2006/2007:

Average weekly biomass measurements for 21 weeks are plotted in Figure 2.13. As measurements were made on only ten stems each week, determining whether the stem height data were normally distributed was not achievable. Except for the first week, stem height and diameter changes followed the same trends. Leaf count and LAI values also exhibited similar patterns. Pearson Correlations were carried out, at 95% confidence levels, to quantify these relationships. Stem height and diameter were highly correlated (r value 0.688; $P=0.0001$); leaf count and LAI displayed a slightly weaker correlation (r value 0.485; $P=0.0001$). Average stem heights increased, relative to the start of the experiment, until 14th December, thereafter stem heights returned to almost the same value as the beginning of the experiment, repeating the pattern seen in the biomass tracking study. Maximum average height was recorded on 10th November. Stem diameters showed a mean decrease from the beginning of the measurements (2.77 ± 0.5) to the last recording (2.64 ± 0.5). The average number of leaves per stem more than doubled from the 3rd August until the 10th November (15 leaves). A slight decrease in leaf number was seen over November, major leaf loss was recorded in the December measurements. Maximum and minimum LAI values corresponded to maximum and minimum leaf counts on 10th November and 23rd December respectively.

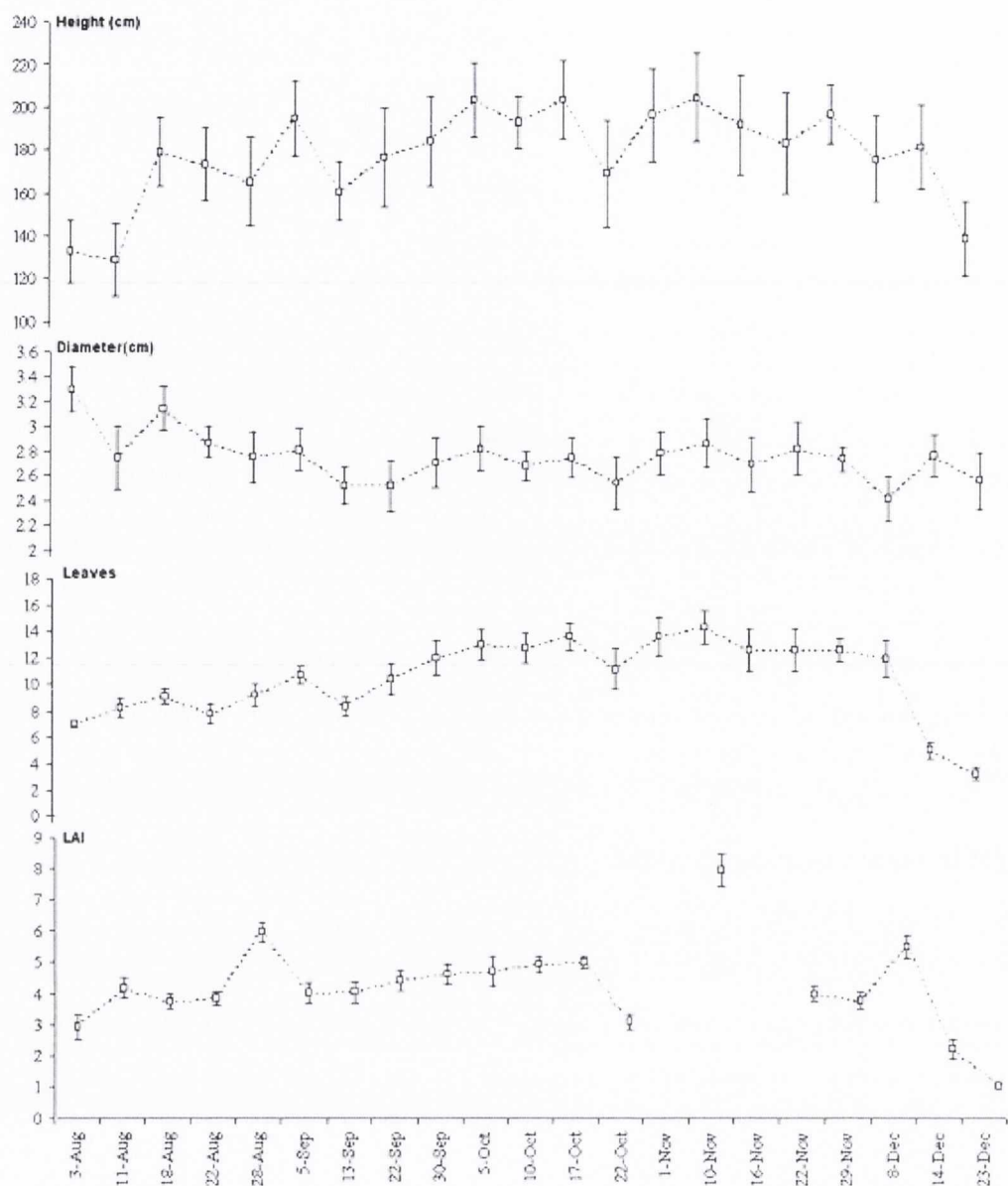


Figure 2.13: Average weekly stem height, stem diameter, leaf count measurements ($n = 10$ plants per week) for the experimental period and derived LAI. Error bars are $\pm$ standard error.

The dry weight of leaf, stem and total above ground biomass was measured for each week and averaged on a monthly basis (Figure 2.14). An increase in all categories was seen from August to November. A decrease in biomass was observed in December with a notable decrease in the leaf component. Maximum average stem dry weights were recorded in November ($17.74 \pm 1.46 \text{ t DM ha}^{-1}$) with minimum dry weights in August ($12.36 \pm 2.06 \text{ t DM ha}^{-1}$). Average leaf dry weights were at their highest in October ($5.87 \pm 0.64 \text{ t DM ha}^{-1}$) and lowest in December ($0.85 \pm 0.28 \text{ t DM ha}^{-1}$).

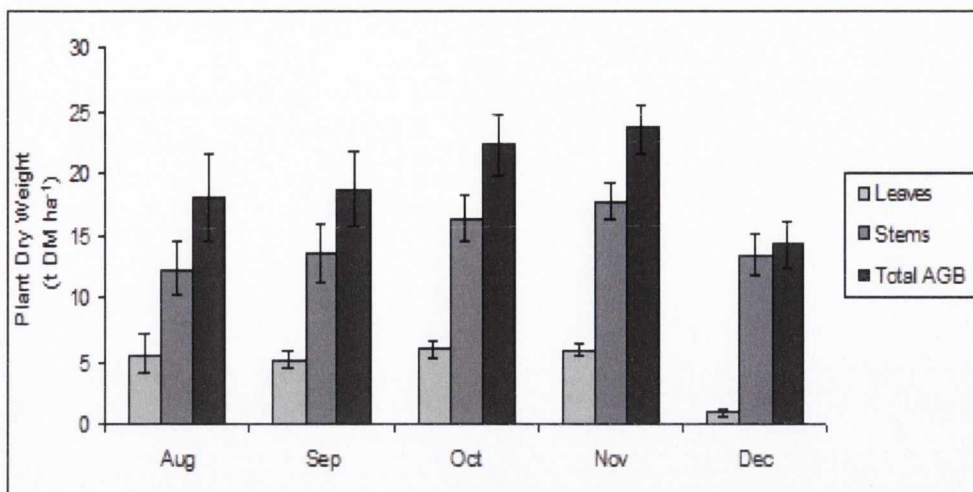


Figure 2.14: Mean monthly dry weight (t DM ha⁻¹) of leaf, stem and total above ground biomass (AGB) (stem + leaf material) of *Miscanthus* from August to December 2006. Error bars are $\pm$ standard error.

2.3.4: (4) Combined above and below ground sampling programme: 2007/2008:

2.3.4.1: Above Ground Biomass:

Normal distribution tests were carried out on the stem height and stem diameter data sets. The stem diameter data displayed regular Gaussian forms for each measurement period and so were analysed as a single data block. The stem height data again showed a ‘shorter’ and ‘taller’ population, each demonstrating normalised distribution independently (Figure 2.15). The shorter population was only present until November; thereafter the entire data set acted as a single population (Figure 2.16). In July the shorter population accounted for 27% of the samples, by December that population had either died or had been amalgamated into the taller group. For analysis purposes, the first four months of stem height data were separated into the two distinct populations and after that, the data were treated as a single population.

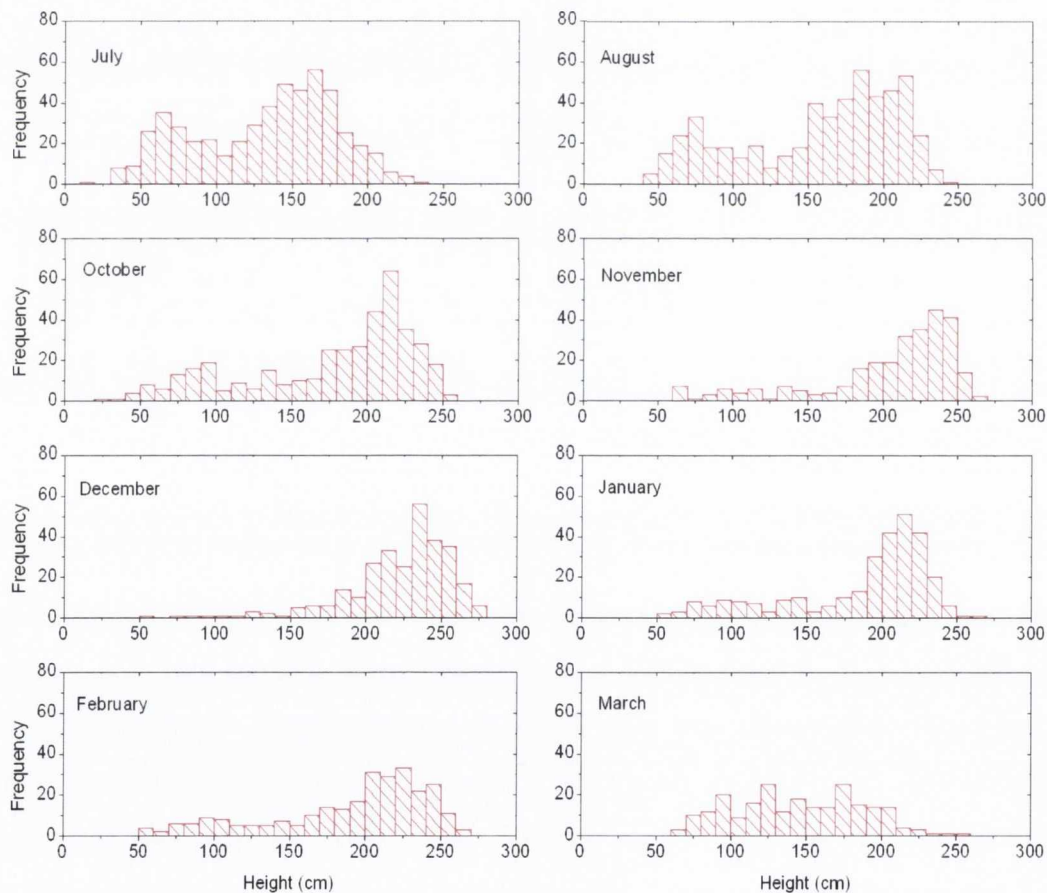


Figure 2.15: Population frequency histograms for *Miscanthus* stem heights from July 2007 to March 2008 (data from each month represents all stems present in six 1 m² quadrats).

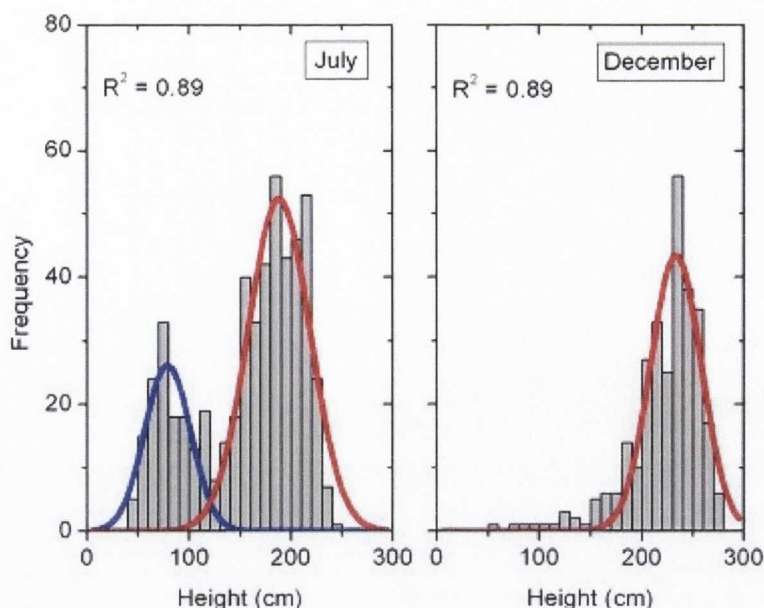


Figure 2.16: *Miscanthus* stem height data showing two distinct populations in July (the shorter population (blue) and the taller population (red)) and only one distinct population in December 2007. In July, the shorter population accounted for 27 % of the samples with the taller population accounting for 73% of the population.

Mean monthly stem heights increased in both populations over time. The taller population decreased from a maximum in December (2.21 ± 0.02 m) to a minimum in March (1.44 ± 0.02 m). A Pearson Correlation test, at 95% confidence, was performed on the height and diameter data for the taller and shorter plants; correlation r values of 0.424 (P value, 0.00002) and 0.569 (P value 0.00001) were obtained for the taller and shorter plants respectively. This indicates a stronger correlation between the shorter plants and stem diameter than that observed in the taller population. Diameter and LAI data showed the strongest correlation (r -0.652; P value, 0.001). Stem diameters increased from October to December whilst LAI showed a decrease during the same period. LAI continued to decrease until March 2008. Conversely, stem diameters increased at this time (Figure 2.17).

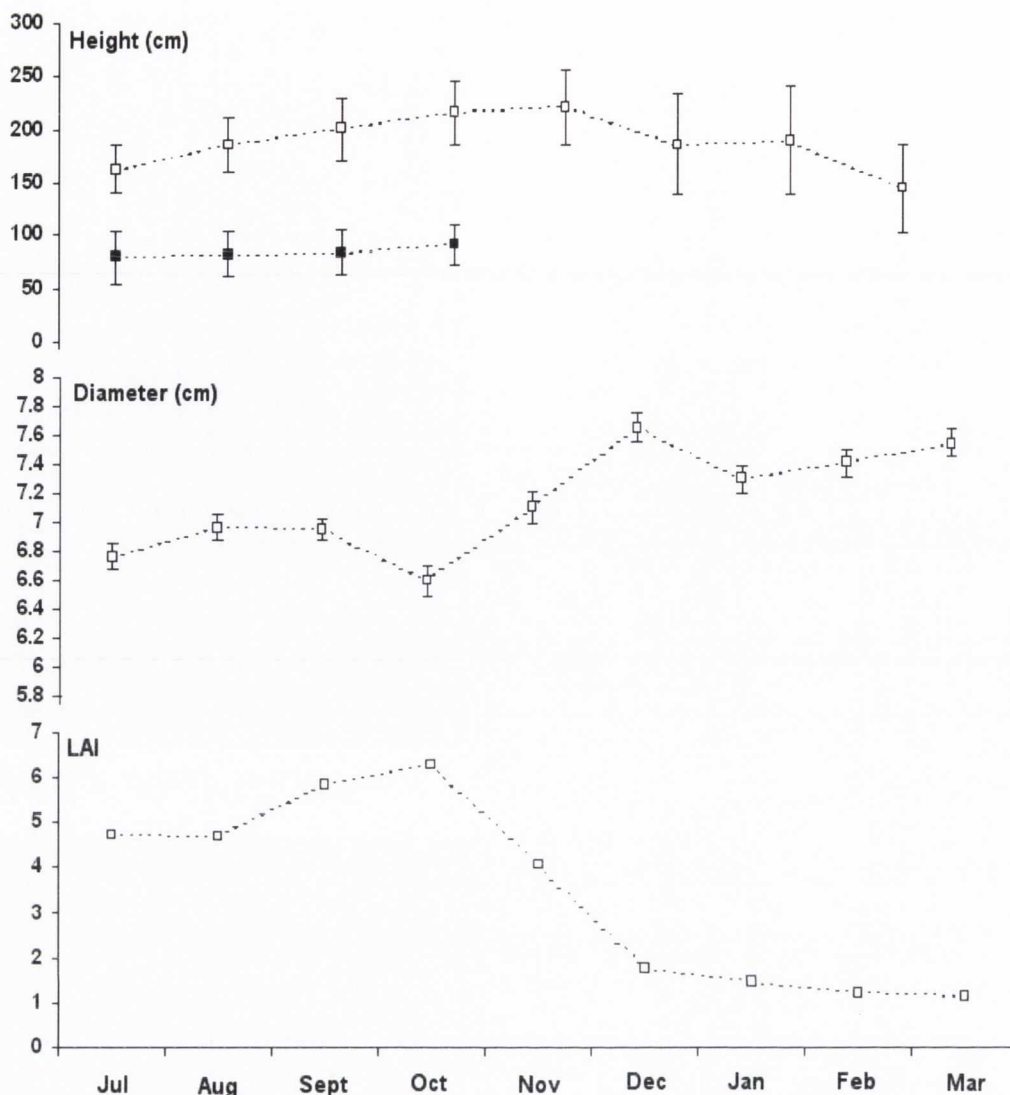


Figure 2.17: Average monthly stem height and diameter measurements and LAI estimates from July 2007 to March 2008 (measurements for each month were performed on all stems present in six 1 m² quadrats). Error bars are $\pm$ standard error

Mean monthly dry weights of all biomass components were calculated. A total above ground biomass of 20.95 ± 5.4 t DM ha⁻¹ was recorded at maximum growth. Leaf and stem biomass increased from the beginning of the experiment to maximum growth in September, after which leaf biomass rapidly decreased monthly until harvesting. Stem biomass also dropped after September but levelled at an average of 6.71 t DM ha⁻¹ month⁻¹ from October to March. Figure 2.18 shows the monthly mean dry weights of stem and leaf material from all the biomass assessment studies carried out in the *Miscanthus* stand from November 2005 to April 2008, demonstrating the differences biomasses between months and years.

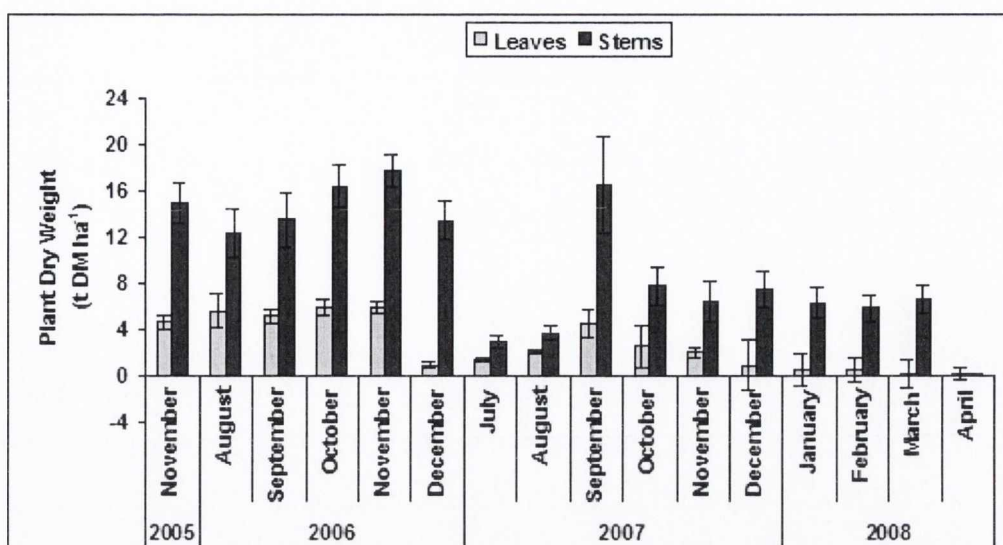


Figure 2.18: Monthly mean dry weights (t DM ha⁻¹) of stem and leaf material from all the biomass assessment studies carried out in the *Miscanthus* stand, in Oak Park Research Centre, from November 2005 to April 2008.

2.3.4.2: The relationship between biomass measurements and standing dry weight:

The stem height and diameter data from July 2006 to March 2008 were compiled. Relationships between stem volume and stem height with standing crop dry weight were noted. For simplicity the *Miscanthus* stems were assumed to be cylindrical; in fact, the cross sectional area of a stem is elliptical (Kaack and Schwarz, 2001). The volume of the *Miscanthus* stems was determined using $\pi r^2 h$. Linear and polynomial functions best described the relationship between stem volume and stem height with plant dry weight respectively. To investigate the potential of these relationships as predictive models for standing dry weight a repeated random sub-sampling validation approach was employed. This method involves randomly partitioning the original data sets into two complementary subsets, fitting a model to one subset, called the training set, and assessing the predictive accuracy of the analysis on the other subset, called the testing set. To reduce variability, multiple rounds of cross-validation were performed using different partitionings and the results were averaged over the rounds. Five training sets were created for both the stem volume/dry weight and stem height/dry weight data sets using 50% of the original data. A linear function best described the relationship between stem volume and plant dry weight ($R^2 = 0.88 \pm 0.004$, $n=5$) (Figure 2.19); while, a polynomial function best described the relationship between stem height and plant biomass ($R^2 = 0.83 \pm 0.009$, $n=5$) (Figure 2.20).

Stem Volume Model:

$$\text{Total plant dry weight (t DM ha}^{-1}\text{)} = [0.0202 * (\text{stem volume (cm}^3\text{)})] - 4.6926$$

Stem Height Model:

$$\text{Total plant dry weight (t DM ha}^{-1}\text{)} = [0.0009 * (\text{stem height (cm)})^2] - [0.0786 * (\text{stem height (cm)})] + 1.7025$$

To investigate how well the models described the data, the testing sets were plotted against the corresponding training sets (Figures 2.21 and 2.22). A linear relationship would indicate the modelled data accurately predict the measured values. The averaged regression co-efficients (n = 5) indicated that the stem volume model accounted for $88 \pm 0.4\%$ of the variation in standing plant biomass; the stem height model accounted $82 \pm 1.4\%$ of the variation in plant dry weight.

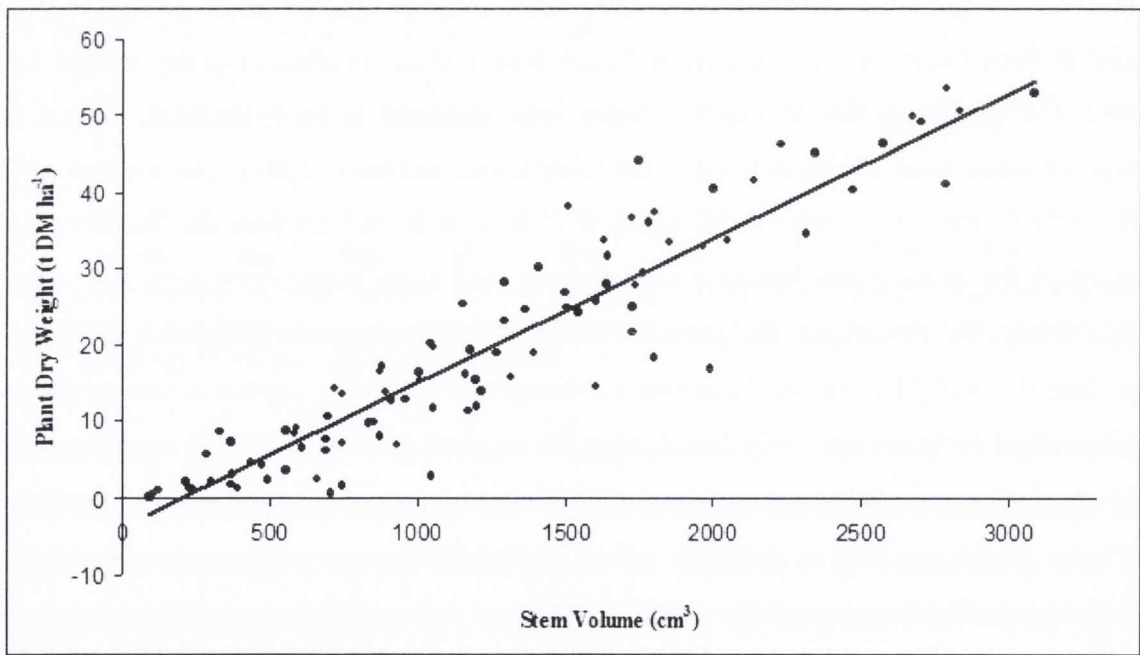


Figure 2.19: A training data subset displaying a linear relationship between volume of *Miscanthus* stems (cm³) and total plant dry weight (t DM ha⁻¹). ($R^2 = 0.88$)

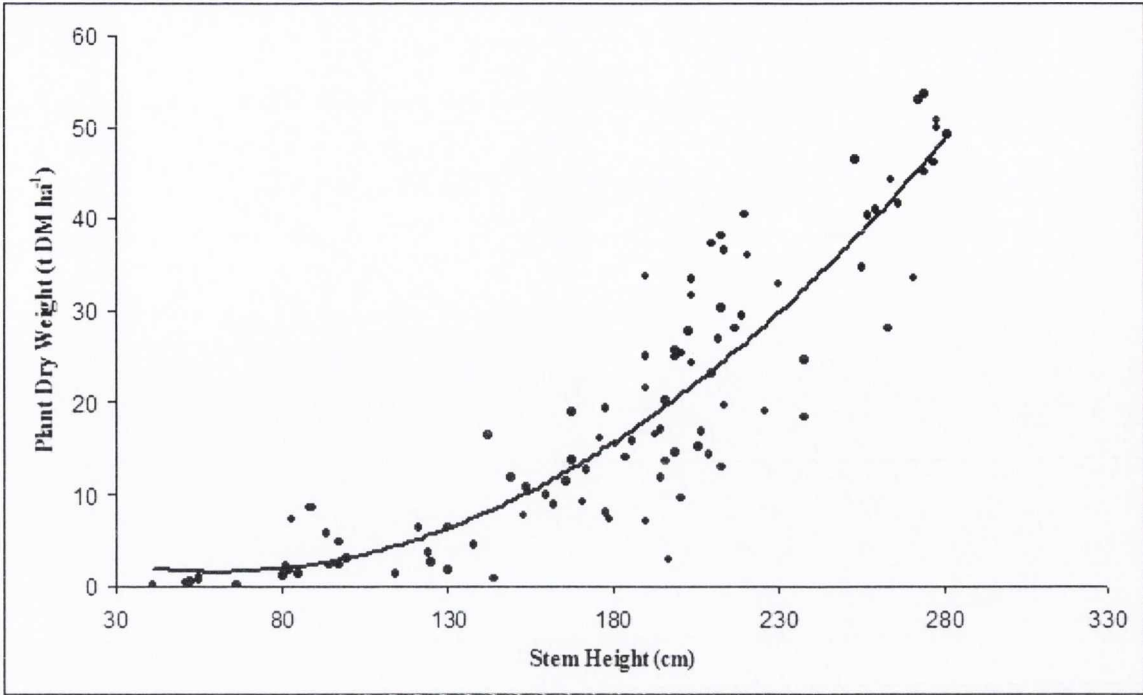


Figure 2.20: A training data subset displaying a polynomial relationship between *Miscanthus* stem height (cm) and total plant dry weight (t DM ha⁻¹). ($R^2 = 0.82$)

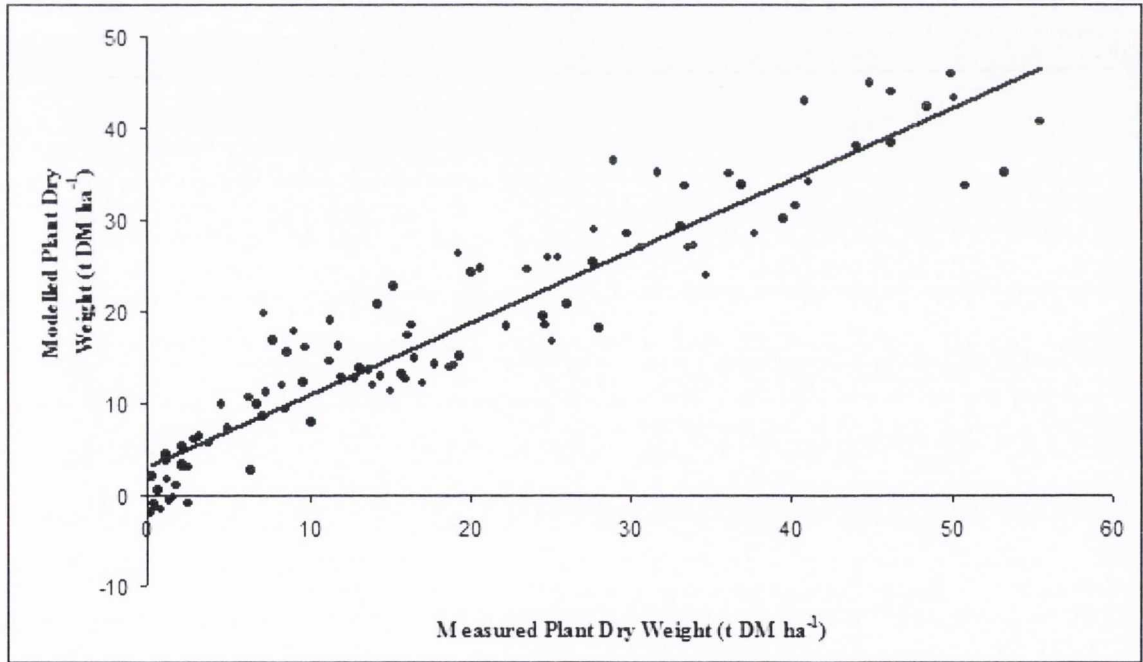


Figure 2.21: Relationship between measured and modelled plant dry weight (t DM ha⁻¹). Modelled data were generated using a simple linear function describing the stem volume/ dry weight relationship from corresponding training data sets. ($R^2 = 0.88$, Slope = 0.78).

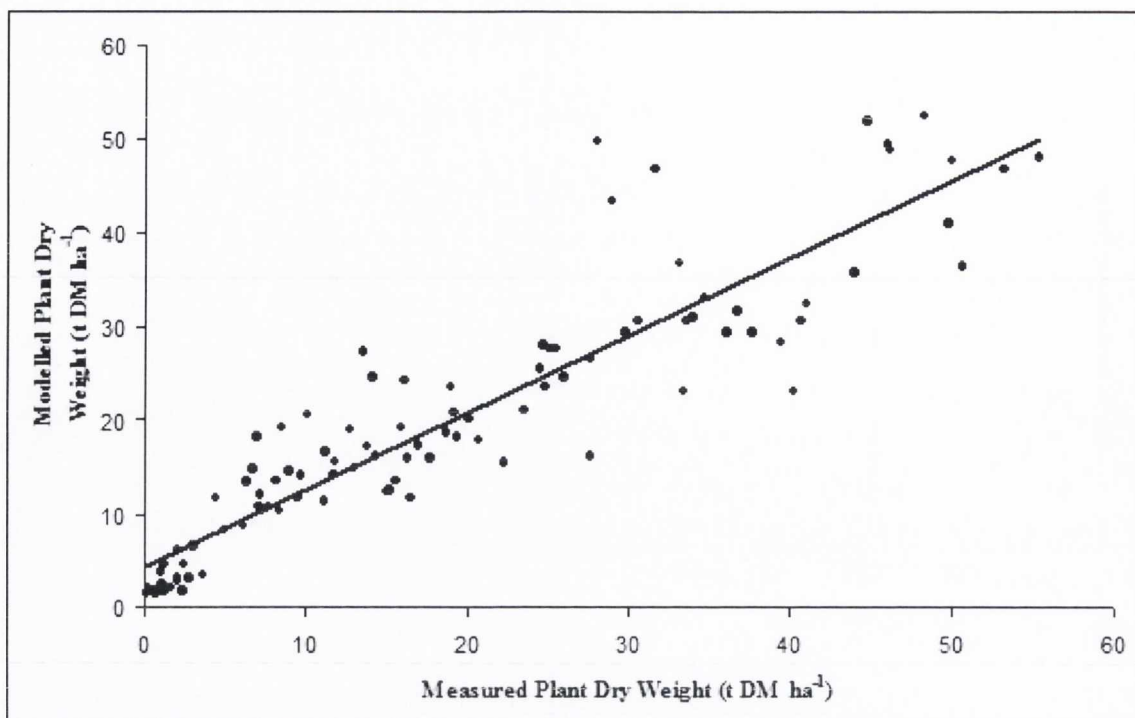


Figure 2.22: Relationship between measured and modelled plant dry weight (t DM ha^{-1}). Modelled data was generated using a polynomial function describing the stem height/dry weight relationship from training data sets. ($R^2 = 0.83$, Slope = 0.82).

2.3.4.3: Below Ground Biomass: Coring Technique:

As root sampling was carried out over 10 months, from July 2007 to harvesting in April 2008, the data were extrapolated out to a full year. Figures 2.23 and 2.24 show the change in dry weights of below ground biomass class and total below ground biomass over the duration of the study period. The below ground biomasses for the 2007/2008 season were determined to be: $6.12 \text{ t DM ha}^{-1}$ of rhizomal material, $1.27 \text{ t DM ha}^{-1}$ of coarse roots and $6.10 \text{ t DM ha}^{-1}$ of fine roots. A total below ground biomass of $13.48 \text{ t DM ha}^{-1}$ was recorded in the 0-30 cm soil depth class; this was 4.8 t DM ha^{-1} less than was recorded in 2005. Assuming 47% of *Miscanthus* biomass is carbon (Harvey, 2007), the potential supply of soil organic matter accumulated by the rooting system in 2005 and 2008 was 8.8 and 6.3 t DM ha^{-1} respectively.

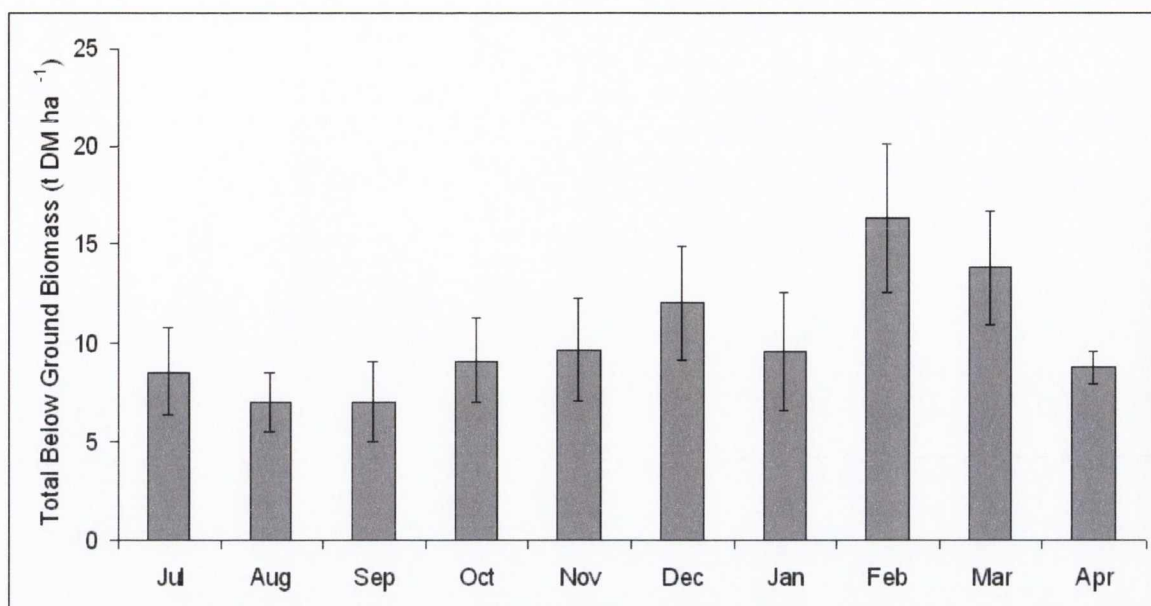


Figure 2.23: Monthly mean dry weights (t DM ha⁻¹) of total below ground biomass (rhizomes + coarse + fine roots) from July 2007 to April 2008. Error bars are $\pm$ standard error.

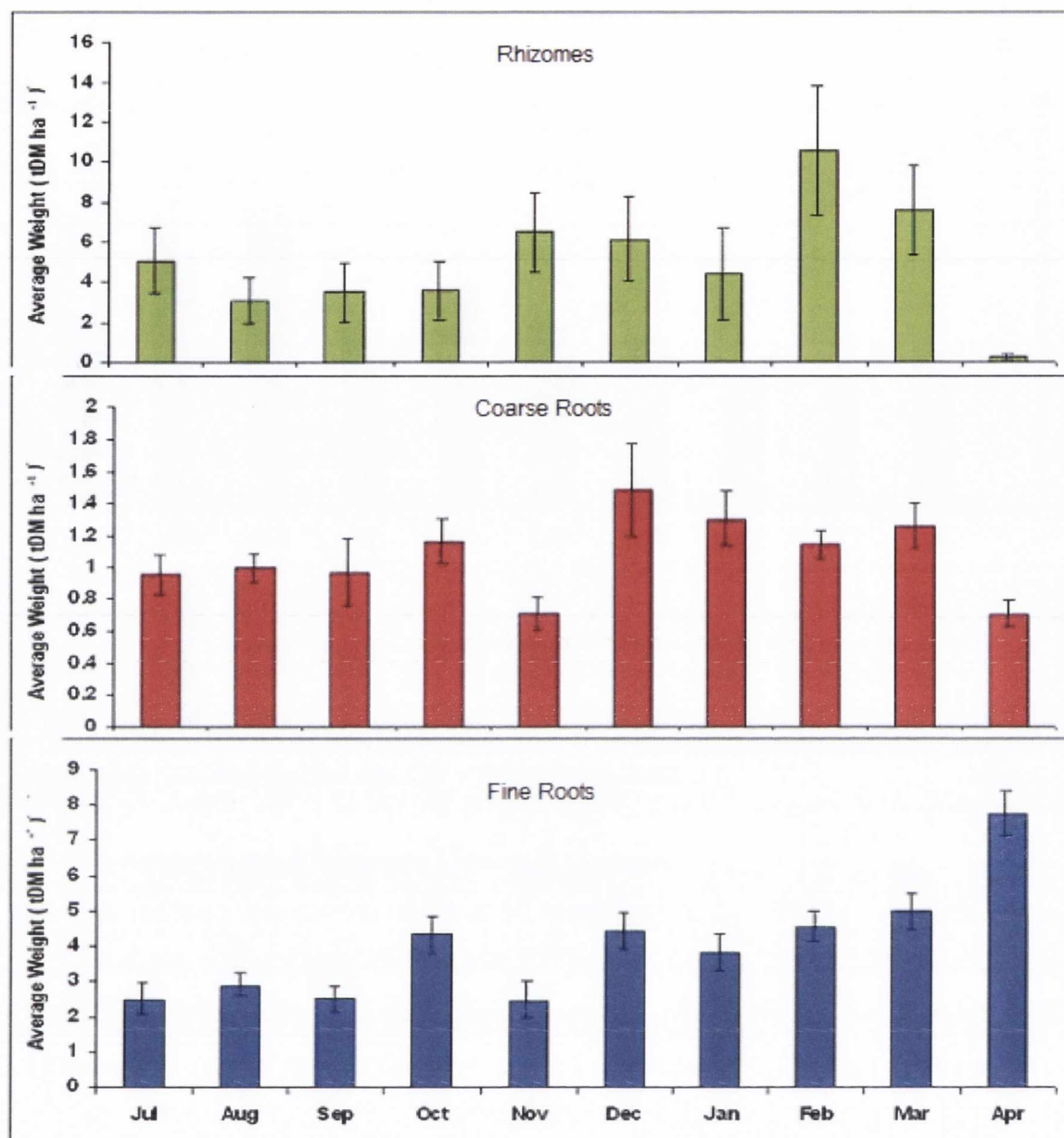


Figure 2.24: Monthly mean dry weights (t DM ha⁻¹) of rhizomes, coarse roots and fine roots from July 2007 to April 2008. Error bars are $\pm$ standard error

2.3.5: Litter Fall:

2006-2007: The shedding of leaves first occurred in the week including the 29th November 2006. High levels of litter fall were recorded on the 8th December 2006 (2.19 ± 0.05 t DM ha⁻¹) and also on the 12th January 2007 (1.36 ± 0.27 t DM ha⁻¹). The experiment continued until harvest time but no further litter fall was recorded after the 19th of January.

2007-2008: Litter fall commenced during the week including the 11th December 2007 and continued until the 16th January 2008. Leaf litter and broken stems were recorded in the litter traps on the 27th February and 18th March, following two extremely windy nights. The data from these two dates were included in the analysis; despite not representing

senescent litter they do represent a natural addition of organic matter into the litter layer. Peaks in litter fall were recorded on the 11th December ($1.11 \pm 0.09 \text{ t DM ha}^{-1}$) and the 8th January ($0.84 \pm 0.07 \text{ t DM ha}^{-1}$) (Figure 2.25).

The total amounts of leaf fall and litter fall rates were 4.65 and 3.08 t DM ha⁻¹ and 9.12 and 3.18 g DM m⁻² day⁻¹ for the 2006/07 and 2007/08 seasons respectively. In addition, six quadrats (1m²) of leaf litter and harvest residues were collected in April 2008; the mean dry weight of post-harvest litter was $7.87 \pm 0.59 \text{ t DM ha}^{-1}$.

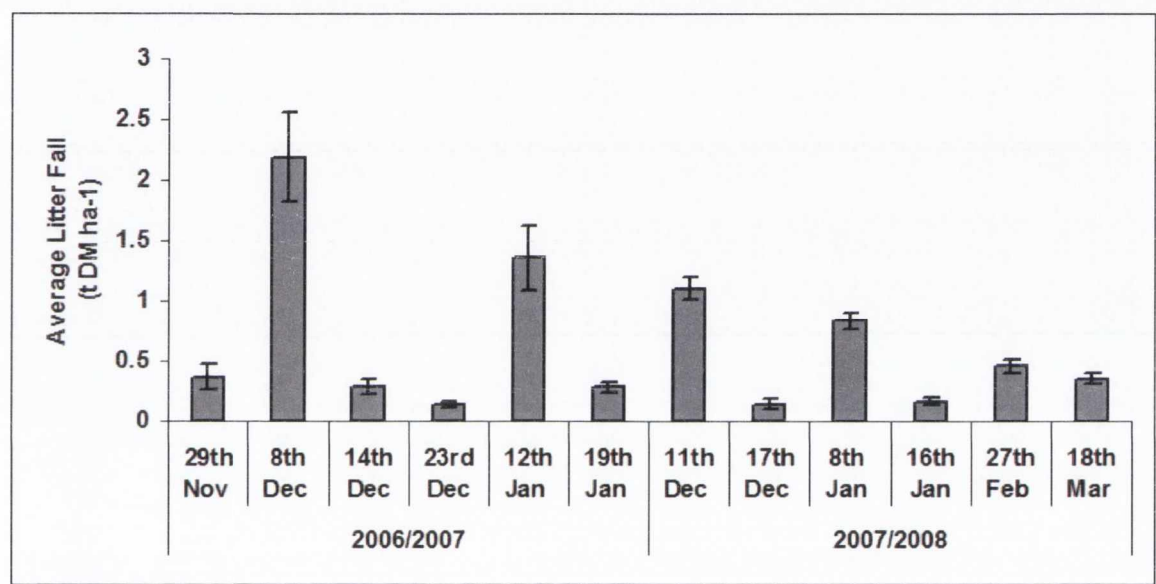


Figure 2.25: Average litter fall in the *Miscanthus* stand over the two sampling seasons. Error bars are $\pm$ standard error.

2.3.6: Litter Decomposition:

Following travel loss and temperature corrections, the rate of decomposition of leaf litter was calculated (Figure 2.26). After an initial drop in biomass over the first thirty days, the rate of decomposition closely follows a simple exponential form with a doubling of biomass reduction every forty days. A month after installation, 6.8% of the litter had decomposed. This was followed by a slower rate of decomposition until July, thereafter the rate rapidly increased; only 69.6% of the original biomass remained at final harvest in September. A decay constant (k value) was calculated using the following exponential decay model, proposed by Olson (1963) and critically evaluated by Wieder and Long (1983).

$$W_t = W_0 \cdot e^{-kt}$$

where W_t and W_0 are the quantities of litter at time (t) in years and at the beginning of the experiment (0) and k is the decomposition constant (yr^{-1}). A decay constant of 0.58 was calculated, meaning that after 1.7 years (approximately 20 months) 30.4% of the litter would remain in the *Miscanthus* field.

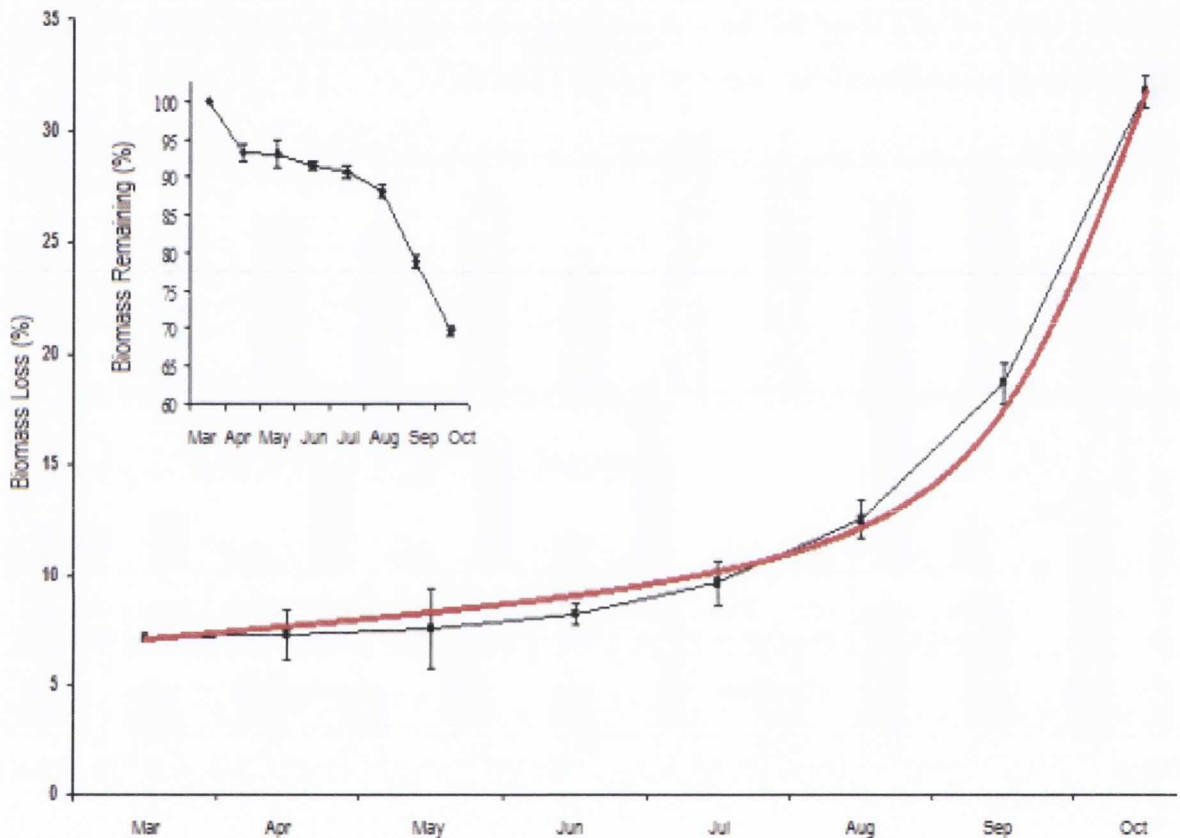


Figure 2.26: Average biomass loss (%) of leaf litter from litter-bags over the experimental period. Error bars are $\pm$ standard error.

2.3.7: Vegetation Surveys:

Appendices 1 to 12 contain the vegetation survey results. Thirty-two weed species were identified in the *Miscanthus* stand during the vegetation surveys (April 2006 to July 2008). Table 2.2 lists all the species recorded and describes their usual habitats. Most of the species are common and abundant in Ireland. Of all the species, only seven were recorded with a cover-abundance of greater than 75% during surveying. These species were *Agrostis stolonifera*, *Cirsium arvense*, *Epilobium angustifolium* L., *Festuca rubra*, *Galium aparine* L., *Lolium perenne* and *Poa annua* L.. Grasses appeared to be best adapted to grow alongside the *Miscanthus*. Data from the permanent quadrats suggested that 88% of all under storey species were recorded at an abundance level of '3' or less on the Braun-

Blanquet scale, corresponding to 50% or less area coverage. The majority of species (43%) were present at level ‘2’ (very numerous or covering at least 5% of the area) or level ‘+’ (25%) (sparsely or very sparsely present, cover very small). The number of under-storey species present, between May 2007 and July 2008, and their cover abundances are shown in Figure 2.27. Below canopy vegetative composition was most diverse in May 2007; diversity decreased until March 2008, thereafter, numbers of species recorded increased to July.

The permanent quadrat surveys continued for 14 months; therefore, it was possible to perform direct comparisons of the same 10 quadrats for May and June in 2007 and 2008. Interestingly, there were fewer plant species present in 2008. In 2007 eight additional species were recorded in the May quadrats compared to the following year; while seven extra species were found the June surveys. The following six species were common in the summer of 2007 but absent in 2008: *Dactylis glomerata*, *Hedera helix*, *Poa annua* L., *Sonchus oleraceus*, *Urtica dioica*, and *Veronica persica*.

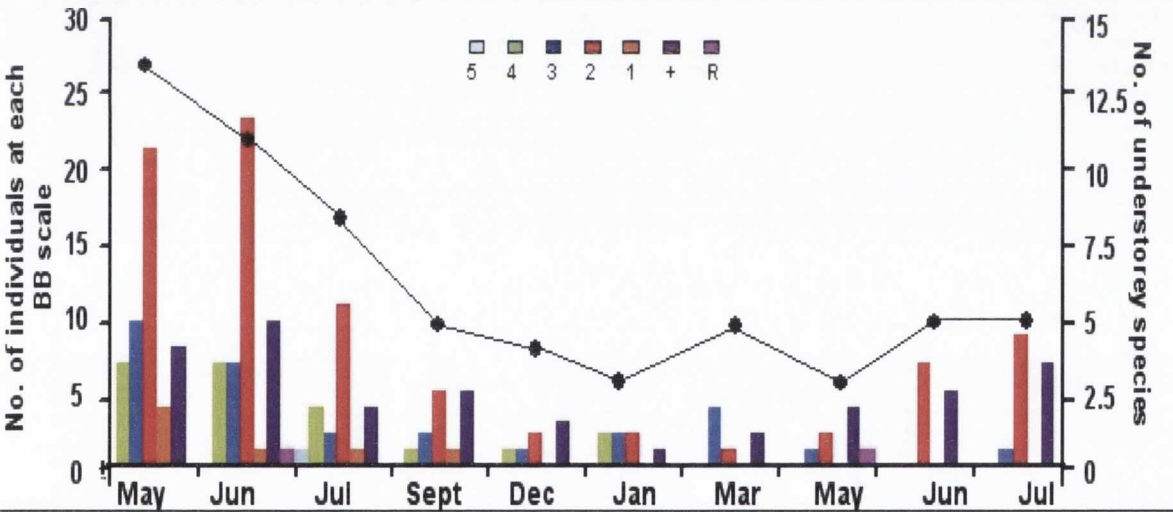


Figure 2.27: The number of under-storey species present (black line) and the number of individuals at each Braun-Blanquet cover abundances between May 2007 and July 2008 in the *Miscanthus* stand.

Table 2.2: All the species recorded in the *Miscanthus* stand during vegetation surveys.

Species	Common Name	Usual Habitat
<i>Aegopodium podagraria</i>	Ground Elder	Shady areas; fertile well drained soils
<i>Agrostis stolonifera</i>	Creeping bent	Damp meadows, ditches, waste places, and rocky sea-shores; abundant
<i>Bellis perennis</i> L.	Daisy	Common on lawns; generally absent from shaded and disturbed habitats
<i>Cirsium arvense</i>	Creeping thistle	Dry pastures and roadsides; abundant
<i>Dactylis glomerata</i>	Cock's foot	Meadows, pastures and waste places; abundant
<i>Epilobium angustifolium</i> L.	Rose bay willowherb	Locally frequent as an introduction on bog margins, railway sidings, roadsides and waste ground in cities
<i>Fagus sylvatica</i> L.	Common beech	Well drained soils
<i>Festuca ovina</i> agg.	Sheeps fescue	Well drained calcareous grasslands
<i>Festuca rubra</i>	Creeping red fescue	Walls, sandy ground, salt marshes and dry waste places; abundant
<i>Galium aparine</i> L.	Cleavers	Hedges, thickets, arable ground and waste-places; widespread and abundant
<i>Geum urbanum</i>	Wood avens	Hedgerows, woodland edges, coppiced woodlands and new or secondary woodlands
<i>Geranium robertianum</i> L.	Herb-Robert cranesbill	Hedges, walls and roadsides; abundant
<i>Glyceria maxima</i>	Reed sweetgrass	Wet areas such as riverbanks and ponds
<i>Hedera helix</i> L.	Ivy	Hedges, woods, walls and rocks; widespread and abundant
<i>Heracleum sphondylium</i> L.	Hogweed	Hedges, meadows and waste ground; abundant
<i>Hypochoeris radicata</i>	Cat's ear	Lawns, pastures and waste ground
<i>Lactuca serriola</i> L.	Prickly lettuce	Waysides and waste ground
<i>Lamium album</i>	White deadnettle	Common; variety of habitats generally on moist, fertile soil
<i>Lolium perenne</i> L.	Perennial ryegrass	Waste places and cultivated fields, on roadsides, in meadows and along borders of woods.
<i>Poa annua</i> L.	Annual meadow grass	Pastures, tilled ground, roadsides and waste places; abundant
<i>Ranunculus repens</i>	Creeping buttercup	Ditches, wet meadows and pastures
<i>Rosa canina</i> L.	Dog rose	Hedges, scrub, woods, roadsides and banks
<i>Rubus fruticosus</i> L.	Bramble	Abundant in hedgerows
<i>Sonchus oleraceus</i> L.	Smooth sow-thistle	Waste-places, roadsides; very frequent
<i>Sphagnum</i> sp.	Species unknown	Unknown
<i>Stachys arvensis</i> L.	Woundwort	wastelands, grasslands and woodland edges
<i>Taraxacum officinale</i> Weber	Common dandelion	Waste ground, roadsides, grassland; abundant
<i>Trifolium pratense</i>	Red Clover	Pastures, thickets, waste places, ruins etc; abundant
<i>Trifolium repens</i>	White clover	Waste ground, pastures, open fields, roadsides, railroads
<i>Urtica dioica</i>	Common nettle	Roadsides, pastures, thickets, waste places, ruins etc; abundant
<i>Veronica persica</i>	Common field speedwell	Arable fields, roadsides and waste ground; abundant in most districts
<i>Vinca major</i>	Greater periwinkle	Woodlands, hedgerows and banks

2.4: Discussion:

The primary aim of this project is to establish a carbon cycle for the energy crop *Miscanthus x giganteus* in Ireland. Determining biomass is a useful method of estimating the quantity of carbon in different plant components, as approximately 47 % of biomass is carbon (Harvey, 2007). This chapter specifically addresses the allocation of biomass into above and below-ground pools. The carbon contained in the various plant components of *Miscanthus* can be significant due to the productivity of the crop and it was important to quantify changes in these pools over time. An assessment of biomass and carbon storage is of particular importance in relation to Article 3.4 of the Kyoto Protocol, where the potential mitigation of CO₂ emissions into biomass is detailed.

2.4.1: Above Ground Biomass:

Productivity data is important when considering the viability of an energy crop; however most of the published data relate to young *Miscanthus* trials (2-5 years old) (Heaton *et al.*, 2010). The productivity of longer established crops is of great importance for determining how long the crop remains economically viable. Heaton *et al.* (2004) calculated an average harvestable *Miscanthus* yield of 22 t DM ha⁻¹, based on 97 observations in the literature, excluding plants aged 1 to 3 years to avoid low yields during establishment. Table 2.3 shows the considerable variation in biomass yields reported in the literature. The harvested yields for the *Miscanthus* stand in Oak Park from 2003 to 2011 were shown earlier in Table 2.1 and ranged from 5.15 to 10.17 t DM ha⁻¹. Interestingly the highest yield for *Miscanthus* in Oak Park was recorded in 2011 when the crop was 17 years old. This is only half of the average yield reported by Heaton *et al.* (2004) but is similar to yields recorded in Cashel, Co. Tipperary (Clifton-Brown *et al.*, 2007) and in the U.K. (Beale and Long, 1997) which would be under similar climatic conditions.

Maximum above-ground biomass at the experimental site was recorded in November 2006 and September 2007. Maximum biomass was not directly correlated to highest mean air temperature or solar radiation; however, in both years the maximum yields were recorded following the warmest month of the year. Maximum biomass yields at the peak of the growing season were 23.60 and 20.95 t DM ha⁻¹ respectively. These yields fell within similar ranges from some published European studies: 7.69 to 27.85 t DM ha⁻¹ (Table 2.4). The comparatively high summer yields at the Oak Park site suggest that crop age (crop established in 1994) is not adversely affecting productivity.

Table 2.3: Demonstrating the range of *Miscanthus* biomass yields reported within the literature.

Country of <i>Miscanthus</i> Trial	Range of Biomass Yields Reported (t DW ha ⁻¹)	References	Reference Key
Ireland	4-20	1	1 Clifton-Brown <i>et al.</i> (2007)
U.K.	8-30	2	2 Beale and Long (1997)
Portugal	24-30	3, 4	3 Clifton-Brown <i>et al.</i> (2004)
Spain	14-34	5	4 Clifton-Brown <i>et al.</i> (2000)
France	42-49	6, 3	5 Lewandowski <i>et al.</i> (2000)
Belgium	15-16	4	6 Tayot <i>et al.</i> (1995)
Netherlands	15	3,4	7 Mantineo <i>et al.</i> (2009)
Denmark	15	5	8 Lewandowski <i>et al.</i> (2003)
Germany	4-30	5	9 Acaroglu and Aksoy (2005)
Switzerland	13-25	5	10 Jørgensen <i>et al.</i> (2003)
Italy	30-32	5, 7	11 Propheter <i>et al.</i> (2010)
Austria	22	5	12 Heaton <i>et al.</i> (2008)
Greece	26-44	5	13 Heaton <i>et al.</i> (2010)
Turkey	12-28	8, 9	
Denmark	4-13	10	
USA: Kansas	12	11	
USA: Illinois	14-44	12	
USA: Mississippi	25-56	13	

Table 2.4: Maximum *Miscanthus* stem and leaf biomass dry weights from published studies and the Oak Park site. * is a mixture of all three age categories.

Age of crop (years)	Location of Study	Biomass (t DM ha ⁻¹)			Reference
		Stems	Leaves	Total Above Ground	
4	Greece	22.15	1.14	23.29	Donalatos <i>et al.</i> (2007)
5		20.98	6.9	27.85	
1	Italy	10	5	15	Ercoli <i>et al.</i> (1999)
2		20	5.6	25.6	
3		20	6.6	26.6	
4		19	6.7	25.7	
1	England	6.99	0.7	7.69	Christian <i>et al.</i> (2006)
2		8.78	1.29	10.07	
3		13.57	0.46	14.03	
4	Germany			10.9	Beuch <i>et al.</i> (2000)
5				10.9	
6				13.175	
4, 5 and 6 *	Germany			10.9	Kahle <i>et al.</i> (2001)
5, 6 and 7 *				11	
6, 7 and 8 *				10.4	
2	Sicily	4.859	16.641	21.5	Cosentino <i>et al.</i> (2007)
3		3.544	12.245	15.76	
13	Ireland	17.74	5.86	23.60	Present study
14		16.46	4.49	20.95	

Miscanthus shoots begin to develop once accumulated daytime temperatures exceed approximately 200-400 °C (Bullard and Nixon, 1999). This generally occurs in late April in Ireland. The density and height of *Miscanthus* stems are important in producing a high yield. Stem heights were measured at the Oak Park site in November 2005, 2006 and 2007 so that comparisons of interannual variation were possible. The stems were, on average, tallest in November 2005 (2.32 m) when compared to 2006 (1.97 m) and 2007 (2.15 m); however, the tallest shoots were not recorded in November for either 2006 or 2007, they were registered in October 2006 (2.08 ± 0.42 m) and in December 2007 (2.21 ± 0.3 m). The pattern of stem height development in 2007 closely resembles that reported by Kaack and Schwarz (2001) with a maximum height achieved in December followed by a linear decrease until harvest. The average stem heights at the end of the growing season in 2006 and 2007 are compared to published data in Table 2.5. The Irish data most closely resemble the 6-year-old Danish *Miscanthus*, (Kaack and Schwarz 2001) and the 3-year-old Sicilian *Miscanthus* (Cosentino *et al.*, 2007). The Oak Park *Miscanthus* stem heights are comparative to the other studies despite its advanced age (13-14 years old); in fact the stems were taller in 2007 than in 2006 so the crop is not displaying any signs of decreased vigour.

Table 2.5: Present study and published *Miscanthus* stem heights.

Age of crop (years)	Location of study	Stem height at end of growing season (cm)	Reference
1	Multiple	269.5	Clifton-Brown <i>et al.</i> (2001)
2	Sicily	258.2	Cosentino <i>et al.</i> (2007)
3		224.4	
6	Denmark	206	Kaack and Schwarz (2001)
5	Denmark	188	Kaack <i>et al.</i> (2003)
13	Ireland	208.4	Present Study
14		221.5	

An interesting observation was made when analysing the stem height data. Two distinct height populations were found in the 2006 and 2007 data. For convenience the populations are referred to as the ‘shorter’ and ‘taller’ groups. The ‘shorter’ population has fewer individuals than the ‘taller’ group in all cases but still contained a significant proportion of the entire population: 27% of all the samples in July 2007 and 14% in December 2006. Size inequality in plant monocultures is strongly influenced by density and intraspecific competition (Schwinning and Weiner, 1998). It is likely that the majority of *Miscanthus*

stems emerge at a similar time but a smaller number emerge later and the early shoots out-compete the later cohort. Silvertown and Charlesworth (2001) showed that a rapid divergence can occur in plants with different starting sizes and in this manner two distinct populations can develop. The conversion of the frequency histograms for stem height from two Gaussian forms in July 2007 into a single logarithmic distribution in December 2007 shows that the 'shorter' plants were out-competed by the 'taller' ones and died-back over the winter months.

Stem diameters were measured to evaluate their potential use as a productivity estimate. Unfortunately, the diameters did not show large variations over the measurement periods, approximately 65% of the population in 2006 did not exhibit any significant change in stem diameter. Stem diameter measurements are only occasionally reported. The average diameter reported ranged between 8.8 and 9.2 mm (Kaack and Schwarz, 2001; Kaack *et al.*, 2003). The average stem diameter at the Oak Park site ranged from 2.4 cm to 3.5 cm. There is quite a clear difference between these ranges. Two possible reasons for this are the Danish studies measured the smaller of the diameter axes, *Miscanthus* stems are elliptical and so have two diameter readings, or alternatively the younger *Miscanthus* stems (6 and 5 years old in the two above studies respectively) were considerably thinner as the plantations were only establishing. In this study a correlation r value of 0.688 ($P=0.0001$) existed between plant height and stem diameter, suggesting that if the younger *Miscanthus* plants were smaller than the older stand in Oak Park, the stem diameters would correspondingly be lower.

Determining the number of leaves per stem is important for assessing the input of carbon into the system through litter fall. LAI measurements can be used to determine when the crop achieved maximum canopy closure and over both campaigns, leaf numbers and LAI increased over the growing season until late October – early November, after which leaves began to senesce and the canopy began to open. Maximum LAI values in the literature were recorded between 7 and 8 (Cosentino *et al.*, 2007; Petrini *et al.*, 1996). A maximum LAI range of 6.4 -7.8 was recorded in October 2007 and November 2006 at the Oak Park site.

2.4.2: Below Ground Biomass:

Below ground biomass was sampled through full extraction in 2005 and through coring in 2007. There is no standardised sampling depth in root biomass studies; the depth selected must be sufficient so it can be assumed to represent practically all of the root system

(Brown, 2002). The preliminary study carried out in November 2006 suggested that the 30 cm depth was adequate. Figure 2.25 shows the relative contributions of stem, leaf and the below ground organs to total biomass. In November 2005 and 2007 the below ground data was remarkably similar in both years, with 36% of the total biomass being attributed to rhizomal material in each case. The coarse roots were also very similar with a 1% difference between the studies; fine roots showed the greatest differences (7 to 14%). The similarities imply that the coring method did not underestimate the rooting material despite its limited sampling potential; however, as other variables such as time and climatic effects are not taken into account a direct comparison of the two below ground biomass removal techniques could not be achieved.

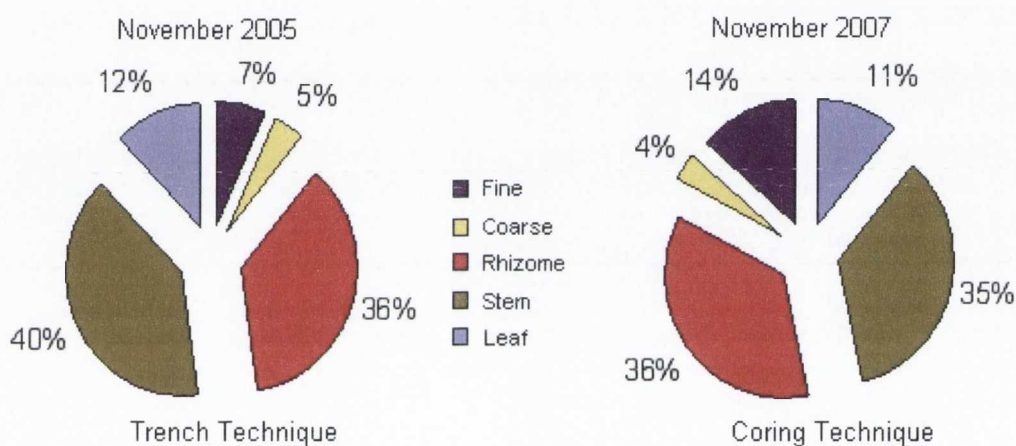


Figure 2.25: The relative contributions of stems, leaves, rhizomes, coarse and fine roots in November 2005 and November 2007 in the *Miscanthus* stand in Oak Park Research Centre, Co. Carlow.

At the Oak Park site, 96.62% of the below ground biomass of the *Miscanthus* plants were located in the upper 30 cm of soil. In a neighbouring *Miscanthus* stand in Oak Park, Albanito (2009) found that the vertical distribution of the *Miscanthus* rooting system was confined to the top 60 cm of soil, with 82% being found in the top 30 cm. Yano and Kayama (1975) reported that in Northern Japan *Miscanthus* had a rooting depth of approximately 120 cm; while in Western Germany, Neukirchen *et al.* (1999) found that *Miscanthus* roots reached a maximum depth of 250 cm, with 30% of the root biomass constrained to the upper 30 cm. The rooting system of the *Miscanthus* under investigation closely resembles the Albanito (2009) findings. It is likely that differences in soil types and soil conditions (such as texture, compaction and nutrient availability) can account for the disagreement in rooting depths between the studies. Christian and Haase (2001) reported that shallow soils reduce productivity; however, Clifton-Brown (2007) demonstrated that *Miscanthus* yielded 15-20 t DM ha⁻¹ yr⁻¹ on soil with a depth of only 40 cm.

In 2007/2008, using soil coring, the average annual rhizome yield was calculated to be 6.108 t DM ha⁻¹ and the average root yield (fine + coarse) was 7.36 t DM ha⁻¹ yr⁻¹. When compared to other published studies (Table 2.6) the rhizome yields are quite low and the root contribution is quite high. These values have been averaged over the experimental period, by reporting instead below ground yields in February 2008, at the peak of rhizome biomass, the values would be 10.59 and 6.71 t DM ha⁻¹ yr⁻¹ for rhizomes and roots. These values are somewhat closer to those given by Kahle *et al.* (2001) for a more mature *Miscanthus* stand; highlighting the need for clarifying the time of year that reported below ground yields were determined as the time of the year may be of great significance. Beuch *et al.* (2000) suggested that, in the long term, rhizomes and roots could provide as much as 9.1 t DM ha⁻¹.

Table 2.6: Present study and published *Miscanthus* rhizome and roots (coarse + fine) biomass dry weights.

Age of crop (years)	Location of Study	Biomass (t DM ha ⁻¹ yr ⁻¹)		Reference
		Rhizome	Roots	
1	England	4.2	1.96	Christian <i>et al.</i> , 2006
2		6.71	1.99	
3		10.32	2.08	
4	Germany	16.85	5.5	Beuch <i>et al.</i> , 2000
5		14.7	4.26	
6		14.45	7.1	
4, 5 and 6 *	Germany	16.85	5.5	Kahle <i>et al.</i> , 2001
5, 6 and 7 *		14.7	4.3	
6, 7 and 8 *		14.45	7.1	
13	Ireland	6.11	7.4	Present study

* Combination of years

The below ground biomass of *Miscanthus* has a defined growth cycle. Generally, a drop in biomass is recorded at the beginning of the season (April to July) (Beale and Long, 1997) (April to August) (Himken *et al.*, 1997). Approximately one month after the beginning of shoot elongation, roots begin to grow (Koike *et al.*, 1975). Roots continue to grow until late October (Midorikawa *et al.*, 1975) when they reach maximum root dry weight (Yano and Kayama, 1975; Neukirchen *et al.*, 1999). Root biomass decreases over winter until reaching similar biomass weights as at the beginning of the season (Himken *et al.*, 1997). Beale and Long (1997) reported a net increase in rhizome mass of 20% over a year; while, Himken *et al.* (1997) demonstrated an annual increase in biomass of 25% (5 t DM ha⁻¹). A much lower increase of 2.6% (0.22 t DM ha⁻¹) was recorded at the Oak Park site. In addition the regular pattern of root biomass change was not observed at the study site. An

increase in biomass was noted from August to December, followed by a decrease in January, a maximum weight gain in February ($12.08 \text{ t DM ha}^{-1}$) and a decline towards the end of the experimental period. Possible reasons for the differences between this study and those previously published include the age differences between the crops investigated and the spatial limitation of coring relative to complete root extraction techniques. At the time of coring, the *Miscanthus* at the Oak Park site was 13-14 years old; this was between 8-11 years older than the crops examined in other below ground sampling. As crops age their productivity can lessen, which in turn can reduce the quantity of carbohydrates available for translocation into below ground structures at the end of the growing season, thus leading to lower levels of weight gain in the rooting system. Furthermore, the fertility of the soil may be diminished after 14 years of continuous growth, thereby reducing crop productivity above and below ground. The coring technique also only extracts a small proportion of the soil volume within a sampled quadrat. It is possible that all, or some, of the rooting categories were under-represented due to the limited spatial sampling that coring permits. For instance, in April only 3% of the cored material was rhizomal; it is possible that the plant rhizomes were not fully sampled in these quadrats.

2.4.3: Root: Shoot Ratios:

Root: Shoot ratios provide an estimate of total biomass that can be used in carbon budgeting. In *Miscanthus* studies Rhizome:Shoot ratios are employed. Himken *et al.* (1997) reported a Rhizome: Shoot ratio of 0.6 at maximum shoot biomass in September and a ratio of 1.0 at harvest in March. Greef (1996) reported a range of ratios between 0.5 to 0.9 in a four-year old *Miscanthus* stand. At the Oak Park site the average Rhizome: Shoot ratio at maximum shoot biomass was 0.87 and at harvest was 1.6 (averaged from 2006 and 2007 data). The Oak Park ratios are greater than the published ratios. This is not completely unexpected as the Oak Park site has had more time to develop an extensive rooting system and so naturally has greater Rhizome: Shoot ratios. An alternative explanation is that differences in assimilation distributions exist between the study crops.

2.4.4: Using Above Ground Measurements to Estimate Dry Matter Yields:

Relationships between stem volume and stem height with standing dry weight were observed, as established through destructive harvesting. Linear and polynomial functions best described the relationship between stem volume and stem height with plant dry weight respectively. To investigate the potential of these relationships as predictive models for standing dry weight a repeated random sub-sampling validation approach was employed.

The averaged regression co-efficients ($n = 5$) indicated that the stem volume model accounted for $88 \pm 0.4\%$ of the variation in standing plant biomass; the stem height model accounted for $82 \pm 1.4\%$ of the variation in plant dry weight. The stem volume model proved more accurate at predicting standing dry weight but does require the measurement of both stem height and stem girth. Measuring stem height alone still provided a good corresponding estimate of the dry weight of the crop, if it was harvested at that time. Stem height measurements are both quick and easy to perform; therefore, despite the lower predictive accuracy of the stem height model, it may prove more appropriate for practical use.

As the analysis was carried out solely at the Oak Park site, the two models may not be applicable in areas with significantly different climatic conditions or on stands within a different age range. Nevertheless, the models are important as they represent the first attempt in providing reasonable estimates of standing dry weight for *Miscanthus* plants. It is hoped that the *Miscanthus* farming community could use this technique to determine standing yields. The benefit of the models is that non-destructive measurements can be made in the field and can then be converted into a realistic standing dry weight estimate. Both models are based on simple empirical measurements to encourage use.

2.4.5: Litter Fall:

The two litter fall campaigns yielded similar patterns: maximum litter fall occurred over the week of 8th December with a secondary inundation over the week of 12th January during 2006/2007 and two parallel peaks in litter fall were recorded during the 2007/2008 season in the weeks that included 11th December and 8th January. Senescent leaves stopped falling in mid January in both years. *Miscanthus* leaf senescence occurs following the first frost of the winter. In 2006, temperatures of $-2.8\text{ }^{\circ}\text{C}$ and $-1.5\text{ }^{\circ}\text{C}$ were recorded on the 3rd and 4th of November. In 2007, temperatures dropped below zero for the first time in winter months on the 23rd and 24th of November ($-2.8\text{ }^{\circ}\text{C}$ and $-0.8\text{ }^{\circ}\text{C}$). The earlier on-set of frost in 2006 is most likely responsible for the earlier litter fall in that year. Regardless of the commencement date, litter fall had fully ceased by the 16th of January in both cases. The litter fall of 4.65 and 3.08 t DM ha^{-1} exceeded those reported by Christian and Riche (1998) of 2 t DM ha^{-1} for a young *Miscanthus* stand (age not specified).

There was markedly less litter fall in 2007/2008 (3.08 t DM ha^{-1}) compared to 2006/2007 (4.65 t DM ha^{-1}) despite two storm periods when leaf litter fall was accelerated; the

corresponding litter fall rates were 3.18 and 9.12 g DM m⁻² day⁻¹. Based on above-ground biomass measurements, the average number of leaves present on a *Miscanthus* plant (n=100) in September 2006 and 2007 were 9.74 and 7.84 leaves respectively. This suggests that there was less leaf material present in 2007/2008 and hence the lower litter fall quantities. This is also reflected in the annual average LAI for the two years with a larger average LAI in 2006 (4.2) compared to 2007 (3.4). Interestingly, a higher harvest yield was recorded in 2008, showing that greater leaf production does not necessarily predict greater crop yields.

2.4.6: Litter Decomposition:

The rate of litter decomposition is determined largely, by climate, the decomposing organisms present, and the chemical quality of the material (Fog, 1988). Neither temperature nor moisture content were recorded at the litter-bag sampling sites so the effects of either factor on the decomposition rate cannot be assessed. The litterbags were subject to field conditions and during the period of the experiment no unusual weather conditions were recorded. As soil water content is a strong determinant in biomass decomposition, most importantly no drought conditions developed. It is worthy of mention that the metallic nature of the litter-bag used in this study may have altered the litter micro-environment predominantly through heat retention. There is a scarcity of *Miscanthus* litter decomposition experiments in the literature, even though it provides important information regarding the supply of carbon and nutrients into the ecosystem. Most published work is on *Miscanthus sinensis* (Osono, 2010; Gams *et al.*, 1999) or *Miscanthus oogiformis* L. (Dresboll and Magid, 2006) providing limited comparative studies.

Based on the exponential decomposition decay constant ($k=0.58$), described in section 2.3.6, almost 70% of all the freshly fallen *Miscanthus* litter will mineralise within approximately 20 months, providing steady carbon and nutrient recycling over the following growing seasons. This decay constant falls within the range of reviewed litter decomposition rates by Aerts (1997); based on 44 study cases, k values varied between 0.35 – 2.33. The *Miscanthus* decay constant was most similar to those reported for temperate regions. The initial rapid decomposition observed in the first 30 days after installation relates to the decomposing of readily available labile compounds in the litter by micro-organisms. The subsequent plateaux in decomposition, corresponds to the decreased amount of labile carbon available and the slower decomposition of the recalcitrant material. The exponential increase in the decomposition thereafter is associated with

increased access to compounds over time. Similar patterns have been observed in a number of ecosystems (Berg, 2009; Moore *et al.*, 1999; Aerts, 1997). The organic matter released by decomposition can be respired by the micro-organisms, leading to increased CO₂ release, or it can be sequestered into the soil in labile or recalcitrant pools.

There was little variation in biomass loss between litter-bags sampled at the same time; this suggests that the positioning of the bags did not greatly affect the decomposition rates. It can thus be assumed that the exponential model is a good predictor of litter decomposition for the entire *Miscanthus* stand, when water is not a limiting factor. Harvesting produces large amounts of residues that are left to decompose on the soil surface. These residues can prove to be more substantial than natural litter fall and potentially act as a major component in the carbon cycle of *Miscanthus*, supplying large amounts of organic matter into the soil. In April 2008, the detritus material on the field post-harvest measured 7.87 ± 0.59 t DM ha⁻¹. Assuming *Miscanthus* biomass contains 47% carbon (Harvey, 2007) then the potential supply of soil organic matter was 3.7 t C ha⁻¹ in 2008; Beuch *et al.* (2000) reported a similar value of 3.1 t C ha⁻¹ yr⁻¹ in a 4-8 year old *Miscanthus* stand in Germany. Using litter fall data for the 2007/2008 season, the rate of litter decomposition¹, as described by the exponential model, and the post-harvest data it was possible to calculate the amount of harvest residue left on the field in 2008. Harvest residue was defined as material on the ground after harvesting less the material on the ground before harvesting. Remarkably the harvest residue was 5.04 t DM ha⁻¹, consisting of broken stems, stem stubble and leaves, remaining on site. This is a substantial loss to the farmer in terms of crop yield; conversely, it is beneficial to ecosystem by providing a substantial input of organic matter (2.37 t C ha⁻¹).

2.4.7: Vegetation Surveys:

The low number of species and their relatively low abundance levels suggest *Miscanthus* out competes most under-storey species. The drop in species from May to October coincides with canopy closure and reduced under-storey light levels. Following senescence in December light penetration is greatly increased but the heavy litter fall blankets the soil and prevents weed development. The increase in species numbers following May in 2008 is attributed to a combination of lower litter levels following winter decomposition and the relative openness of the *Miscanthus* canopy at this time. The low abundance levels of

¹ The decomposition rate was determined based on measurements made from March to September when the climatic conditions would be different from those in December to April. Therefore, the decomposition calculation here, may underestimate the amount of litter on the ground at the time of harvest.

under-storey species suggests that their relative contributions to net ecosystem exchange would be minimal, particularly during the growing season when canopy closure reduces the abundance of species abundance. Grasses were the most dominant type of vegetation found in the *Miscanthus* stand. Numerous studies have shown grasslands to be both sinks and sources of CO₂ (Flanagan *et al.*, 2002; Hunt *et al.*, 2004; Novick *et al.*, 2004). However, most studies are carried out on grazed and intensively managed grasslands. Byrne *et al.* (2007) reported a net ecosystem exchange of $2.9 \pm 0.5 \text{ t C ha}^{-1} \text{ yr}^{-1}$ from an intensively managed *Lolium perenne* L. grassland. Leahy *et al.* (2004) recorded an annual carbon uptake of 9.45 t C ha^{-1} in a grazed *Lolium perenne* L. field, both studies were located in Co. Cork. It is difficult to extrapolate from the literature a meaningful analysis of the carbon sink or source strength of the natural grass communities in the *Miscanthus* stand. The possible contribution of the under-storey vegetation to the annual net ecosystem exchange of the *Miscanthus* ecosystem, as described by eddy covariance measurements, is discussed in the following chapter.

2.5: Summary:

The most apparent pool of carbon in the *Miscanthus* crop is biomass. Monitoring long-term changes in the different plant organs enables the identification of potential carbon sinks and sources and their variation over time.

- The harvested yields of *Miscanthus* in late March or early April, at the Oak Park site, ranged from 5.15 to 10.17 t DM ha⁻¹ between 2003 and 2011. Maximum above ground biomass was recorded during this study in November 2006 (23.60 t DM ha⁻¹ t DM ha⁻¹) and September 2007 (20.95 t DM ha⁻¹). These results were similar to published data indicating that the age of the *Miscanthus* stand was not adversely affecting crop vigour or productivity.
- *Miscanthus* shoots were tallest in October 2006 ($2.08 \pm 0.42 \text{ m}$) and December 2007 ($2.21 \pm 0.3 \text{ m}$). Two distinct groups of stem heights existed within the populations in both study years; an average difference of 1.07m existed between the two groups. The smaller plants represented 14 and 27 % of the total plant population in 2006 and 2007 respectively. The smaller population were out-competed by the taller plants. *Miscanthus* grew an average of 17 cm from July to October in 2007, representing a growth rate of $0.265 \text{ cm day}^{-1}$.
- Stem diameters displayed little variation or clear patterns of change over the growing seasons. A basic plant volume and dry weight relationship was described

as a predictive tool of standing biomass. It is hoped that the relationship would be used to predict *Miscanthus* biomass non-destructively in Oak Park Research Centre and in the wider *Miscanthus* farming community of Ireland.

- Leaf number per stem and LAI peaked during October and November as the crop canopy closed. Following senescence, both measurements decreased rapidly.
- Litter fall rates were $9.12 \text{ g DM m}^{-2} \text{ day}^{-1}$ and $3.18 \text{ g DM m}^{-2} \text{ day}^{-1}$ over the winters of 2006/2007 and 2007/2008. An average 4.65 and $3.08 \text{ t DM ha}^{-1}$ of leaf litter fell in both years. A decay constant of 0.58 was derived for the *Miscanthus* stand, indicating that 70% of the litter would decompose over 20 months providing a large amount of organic matter into the ecosystem.
- Below ground biomass was sampled as this can provide a significant pool of carbon in perennial crop ecosystems. 96.62% of the below ground biomass was located in the top 30 cm of the soil; this correlated well with the findings in a neighbouring *Miscanthus* field, 82% in the upper 30 cm (Albanito, 2009). During the 2007/2008 season an average of $6.11 \text{ t DM ha}^{-1}$ of rhizome material and $7.36 \text{ t DM ha}^{-1}$ of root material was reported.
- The composition and abundance of weed species in the *Miscanthus* stand were detailed. Species numbers decreased with canopy closure and did not begin to re-establish significantly until May. The low numbers and coverage suggests that *Miscanthus* out-competes the understory species and their relative contribution to net ecosystem exchange would be minimal during the growing season. However, further quantitative studies are needed before any definitive conclusions regarding their contribution are made.

Chapter 3

CO₂ Fluxes of over a *Miscanthus* Crop

3.1: Introduction:

In Chapter 2 the distribution of biomass, in a *Miscanthus* stand, into above and below-ground pools were examined, providing essential variables for the construction of a carbon cycle for the energy crop. In this chapter actual measurements of CO₂ fluxes between the atmosphere and the *Miscanthus* crop are presented. Flux data are useful in completing carbon inventories; eddy covariance provides a direct approach for quantifying the movement of carbon at field-level and has the added benefit of being non-destructive. Plants remove carbon from the atmosphere during photosynthesis and release it back into the atmosphere during respiration; the eddy covariance technique provides a means of measuring this flow of carbon through a crop.

The relationship between increased atmospheric CO₂ concentrations and changes in global climate systems has captured the interest of the scientific community and the wider public. Since the Industrial Revolution human activities, including the combustion of fossil fuels and deforestation, have caused the concentration of atmospheric CO₂ to increase by approximately 35% (NOAA, 2005). CO₂ is a strong absorber of infrared energy. It causes increased global mean surface temperatures by increasing absorption of terrestrial long-wave radiation. The phenomenon is termed the 'Greenhouse Effect'. CO₂, along with water vapour, plays an integral role in climate systems on a regional and global scale (Baldocchi *et al.*, 1996). Proposed responses to Global Warming include carbon mitigation and reduction in greenhouse gas (GHG) emissions. The IPCC define mitigation as activities that reduce GHG emissions and/or enhance the absorption capacity of carbon sinks (Verbruggen, 2007). The Kyoto Protocol (1997) is the main international directive for carbon mitigation. The terrestrial biosphere can play an important role in the mitigation of the Greenhouse Effect. Studies suggest the biosphere can absorb approximately 33% of anthropogenically-derived CO₂ emissions (Schimel, 1995; Watson *et al.*, 2000). Vegetation removes carbon from the atmosphere through photosynthesis, stores it in plant tissues, and releases it through respiration and decomposition. The carbon can also be transferred into longer-term terrestrial or aquatic reservoirs, such as soils or oceans (Schlamadinger *et al.*, 1997). Understanding the flow of carbon through ecosystems enables the quantification of carbon mitigation and estimates can then be made on the

amount of offset fossil fuel emissions (Curtis *et al.*, 2002), which in turn can be used to form policies on future energy and climatic issues.

Traditional methods for measuring carbon fluxes in ecosystems include using leaf cuvettes, plant and branch bags, and soil chambers. These techniques have small sampling areas and the possibility of creating unrealistic micro-climatic conditions (Baldocchi, 2003). An alternative method for measuring carbon fluxes is the eddy covariance (EC) method. EC measures the net ecosystem exchange (NEE) of CO₂ over a large sampling area. Fundamentally, NEE represents the balance between the gross uptake of carbon (gross primary production, GPP) through photosynthesis and gross carbon release by autotrophic (R_a) and heterotrophic (R_h) respiration (total ecosystem respiration, R_{eco}, is the sum of R_a and R_h) (Moffat *et al.*, 2007). Rates of carbon uptake are associated with daytime periods; carbon release occurs continuously over a day but is generally seen as a net release of carbon during periods of low light level, predominately during night-time hours. GPP fluxes are largely dependent on the duration, intensity and interception of PAR (Hanan *et al.*, 2002) as well as the metabolic capacity and pathway of the vegetation (C3, C4 or CAM pathways) (Edwards and Walker, 1983). It is more difficult to describe the drivers in R_{eco} fluxes as they are more diverse; but in general soil and/or air temperature, soil moisture content, humidity, vegetation age and phenology are all factors. EC is one of the most direct and defensible methods available for measuring CO₂ fluxes; however, it requires considerable care during the establishment period, careful selection of measurement sites, maintenance of sophisticated equipment and complex data processing.

3.2: Eddy Covariance:

Eddy covariance (EC) is a micro-meteorological method that provides a direct means for measuring CO₂ by quantifying its turbulent exchange over an ecosystem (Moncrieff *et al.*, 1997) through measuring the covariance between fluctuations in vertical wind velocity and CO₂ mixing ratios (Baldocchi, 2003). Vertical flux densities of CO₂, latent and sensible heat between the atmosphere and the vegetation are proportional to the mean covariance between vertical velocity and the respective scalar fluctuations.

There are two fundamental components in an EC system, a three dimensional sonic anemometer and an infrared gas analyser (IRGA). Sonic anemometers collect information on the turbulent movement of air in the three dimensional planes (u, v and w) using the time of flight principle. A short burst of ultrasound is transmitted from one transducer and

received by a second. The time delay between the transmitted and received burst can be converted into the speed of sound where the distance between the two transducers is known. This conversion more accurately describes the speed of sound in static air plus or minus wind speed. The wind speed is the difference between the measured and actual speed of sound (Burba and Anderson, 2005). In most commercially available sonic anemometers the values of the three wind components and the speed of sound are produced at a rate of 20.8 times per second, with an accuracy of 1.5% below 30 m s⁻¹ and 3% above this speed (Aubinet *et al.*, 2003). At wind speeds above 8-10 m s⁻¹ the speed of sound data becomes increasingly noisy due to a mechanical deformation of the probe head. The measurement of the covariance of the vertical velocity becomes impossible at these high speeds.

There are two types of IRGAs used in EC studies: open and closed path IRGAs. An open path gas analyser has an infrared optical bench that is exposed to the atmosphere; whereby, turbulent fluxes move passively through an infrared beam. In closed path analysers the optical beam is housed within the body of the analyser and is closed to the atmosphere. In this case a mass flow controller draws air from the atmosphere past the optical bench. Both analyser types have their critics. In open path analysers the exposure of the optical bench to the atmosphere allows for the accumulation of water and debris on the lenses, which can distort, refract or decrease the intensity of the infrared beam (Leuning and Judd, 1996). The open nature of the analyser means it is also subject to disturbances by insects or other airborne objects. In addition, the Webb, Pearman and Leuning correction term (Webb *et al.*, 1980) (detailed in a later section) must be applied to data from open path sensors. The typical noise level in an open path IRGA is 0.3 $\mu\text{mol mol}^{-1}$ of CO₂ (Aubinet *et al.*, 2003). EC measurements made using a closed path analyser also have several potential problems, most significantly related to the movement of gas samples from the sampling point to the optical bench. In particular the physical properties of the tubing, through which the sample is drawn, can influence the flow rate and create a lag time between sampling and analysing. Moreover, the act of pushing air through a closed system creates a pressure differential between the optical bench and surrounding atmosphere. This differential can alter CO₂ concentrations and can also cause condensation of water vapour within the sampling tube (Moncrieff *et al.*, 2000).

Regardless of the type of IRGA used, the principle behind the techniques are identical. The IRGA of the EC system can be used for the measurement of a wide range of hetero-atomic

gas molecules including CO₂, H₂O, NH₃, N₂O and CO. Hetero-atomic gas molecules absorb radiation at specific infrared wavelengths, giving a characteristic absorption spectrum (Long and Hällgren, 1993). Homo-atomic molecules do not absorb infrared radiation and so do not interfere with determining the concentration of hetero-atomic molecules. CO₂ has its major absorption bands at 4.25 µm with secondary peaks at 2.66, 2.77 and 14.99 µm. Absorption bands are made up of a series of absorption lines that correspond to the rotational state of the gas molecule. The only other hetero-atomic gas molecule that is normally present in air with an overlapping absorption spectrum is H₂O; both molecules absorb infrared radiation in the 2.77 µm region (Long and Hällgren, 1993).

Swinbank first used the EC technique in 1951; the study was lab-based and lasted only five minutes. Three decades later the first field trials were conducted; amongst the first campaigns were Ohtaki (1984) over rice fields, Anderson *et al.* (1984) over soybeans, Desjardins (1985) over corn, and Anderson and Verma (1986) over sorghum. Initially, EC studies were short-term and normally only carried out during growing seasons (Baldocchi, 2003). Advances in computing, field instruments and data storage led to longer-term experiments. Wofsy *et al.* (1993) conducted the first year-long study of NEE, over a deciduous forest. By 1997 CarboEurope, in Europe, and AmeriFlux, in North America, were established to co-ordinate the outputs from the large number of regional flux measurement sites that had been established (Running *et al.*, 1999; Aubinet, 2000). Subsequently, AsiaFlux, OzFlux, AfriFlux, FLUXNET-Canada, ChinaFlux, USCCC and TCOS-Siberia have also been founded. The FLUXNET database, which collects data from a number of network sites around the world, currently has over 253 EC measurement sites registered (www.fluxdata.org).

3.2.1: Eddy Covariance Theory:

The EC technique has been comprehensively reviewed by Moncrieff *et al.* (1997), Aubinet *et al.* (2000) and Baldocchi (2003), and a short summary is included here. From the outset, it should be made clear that there is currently no uniform methodology for the EC measurements of gaseous fluxes (Burba and Anderson, 2005). Networks, such as FLUXNET, are making progress to standardise a methodology and unify all post-processing steps. The diversity in methodologies hinders synthesis activities because the uncertainties and biases associated with each are still to some extent unknown (Morgenstern *et al.*, 2004).

An EC system measures the fluxes of a gas scalar into or out of an ecosystem. In the case of CO₂, the conservation of mass states that:

$$\frac{d\bar{c}}{dt} = \frac{\partial \bar{c}}{\partial t} + \bar{u} \frac{\partial \bar{c}}{\partial x} + \bar{v} \frac{\partial \bar{c}}{\partial y} + \bar{w} \frac{\partial \bar{c}}{\partial z} - \left(\frac{\partial F_z}{\partial z} + \frac{\partial F_x}{\partial x} + \frac{\partial F_y}{\partial y} + S_{B(x,y,z)} \right)$$

Term	I	II	III	IV
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where the sum of the rate of change of CO₂ mixing ratio (Term I) and advection (Term II) is balanced by the sum of the flux divergence of CO₂ in the three-dimensional components associated with turbulent movement (the vertical (z), lateral (y) and longitudinal (x) directions) (Term III) and the biological sink-strength (Term IV) (Baldocchi, 2003). Note $\bar{u}$, $\bar{v}$ and $\bar{w}$ are the vertical velocities in the x, y and z directions.

Under ideal atmospheric conditions, the scalar concentration and wind velocities are steady over time, so Term I becomes zero (Baldocchi, 2003). It is generally accepted that over a flat terrain and homogeneous surfaces there is no advection (Term II equals zero) and the horizontal flux divergences, $\frac{\partial F_x}{\partial x}$ and $\frac{\partial F_y}{\partial y}$, in term III also equal zero (Moncrieff *et al.*, 2000). Therefore, the above equation simplifies to:

$$\frac{\partial F_z}{\partial z} = -S_{B(z)}$$

By integrating this equation with respect to the height of the sampling point (*h*) you get an expression between the mean vertical flux density measured at height *h* (*Fz(h)*) and the net flux density of scalars into and out of the underlying soil (*Fz(0)*) and vegetation (Liebethal and Foken, 2003).

$$F_z(h) = F_z(0) - \int_0^h S_{B(z)} dz$$

In practice, the *Fz(h)* term is measured with the EC technique. The term on the extreme right hand side represents the storage of the scalar between the soil and the sampling height.

3.2.2: Additional Measurements Associated with Eddy Covariance:

EC measurements require auxiliary meteorological measurements to aid in gap-filling processes and to facilitate investigations into potential environmental factors that affect NEE patterns. The meteorological measurements must be made at the same time as the EC measurements and averaged over the same duration. The following measurements are

routinely made in conjunction with EC measurements; Net Radiation, Photosynthetic Photon Flux Density, Relative Humidity, Atmospheric Pressure, Air and Soil Temperature, Soil Moisture, Precipitation and Ground Heat Flux Density.

3.2.3: Advantages of Eddy Covariance:

There are many advantages of EC over traditional methods of measuring CO₂ fluxes. EC is instantaneous and non-destructive; it does not damage the underlying vegetation or create spurious micro-environments. However, most importantly EC allows the integration of greater spatial variation as the fluxes are derived from a large sampling area, continuously sampling plants of different ages and positions. It would require an exceptionally large campaign of chamber measurements to cover the same variation. Additionally, in Ireland where cloudy skies are frequent, the landscape is often a mosaic of sunlit and shaded patches. This produces highly variable fluxes in a small area and such heterogeneity cannot be sampled sufficiently by chamber measurements alone. However, the traditional methods are not redundant and in many situations EC and chamber measurements complement each other and a campaign that involves the combination of both techniques is advantageous. EC provides NEE data, that is, the sum of a whole community of CO₂ exchanges within the ecosystem. Data from chamber measurements can be used to partition these fluxes into component parts and estimate the relative contribution of the overall NEE value, thereby allowing a more detailed evaluation of the carbon budget of the ecosystem.

Fluxes derived from EC systems can be divided into short- or long-term periods allowing greater in-depth analysis of the data. Short-term measurements (e.g. hourly or daily) can be used to investigate the impact of environmental and physiological variables on carbon fluxes, while long-term measurements (seasonal to annual) can be used to monitor flux responses to changes in climate and phenology as well as inter-annual variation (Baldocchi *et al.*, 1996).

3.2.4: Identifying and Resolving the Limitations of Eddy Covariance:

EC is not without some limitations. Violations of any of the basic assumptions associated with EC, particularly relating to atmospheric stationarity, turbulence levels or surface roughness calculations may invalidate subsequent results. There are also complications when carbon fluxes are not registered by the EC system and gaps ensue. Through careful site selection, equipment installation, sampling techniques and post-processing corrections most violations can be either avoided or their impact greatly reduced. A major constraint

on EC is a process termed the “night-time problem” (Pattey *et al.*, 2006; Wohlfahrt *et al.*, 2005). EC requires turbulent atmospheric conditions, usually based on friction velocity thresholds (u^*), to function correctly (Grace *et al.*, 1996; Goulden *et al.*, 1997; Jarvis *et al.*, 1997; Aubinet *et al.*, 2000; Papale *et al.*, 2006). Uncertainty in measuring fluxes arises when meteorological conditions become stable and there is low frequency eddy formation, as is often the case during the night (Grace *et al.*, 1996). The “night-time problem” is site-dependent and subject to weather conditions (Paw *et al.*, 2000). Some comparative studies between soil chamber and EC measurements have shown that night flux measurements, on calm nights, are clearly underestimated by the EC technique (Black *et al.*, 1996; Law *et al.*, 1999; Twine *et al.*, 2000; Aubinet *et al.*, 2003; Bolstad *et al.*, 2004); but at higher levels of turbulence reasonable NEE estimates are obtained. There is no ecological reason to expect that respiration should be inhibited under calm conditions. Potential reasons for the underestimated fluxes include storage and advection (Mahrt 1998, Paw *et al.*, 2000; Staebler and Fitzjarrald, 2004; Marcolla *et al.*, 2005). Routinely underestimating night-time fluxes is a selective systematic error and can lead to a large over-estimation of ecosystem carbon sequestration if not addressed (Moncrieff *et al.*, 1996; Lavigne *et al.*, 1997).

Carbon storage and advection are two processes that can reduce the accuracy of EC. Carbon released from vegetation through respiration can become trapped under a canopy when the thermal stratification of the atmosphere is stable or turbulent mixing is weak. This carbon is effectively hidden from the EC system and as such is not registered; this typically happens during the night-time. In the morning the stable nocturnal boundary layer is broken with the resumption of convective turbulence. This instigates a burst of CO₂ fluxes from the canopy just after sun-rise (Aubinet *et al.*, 2002; Iwata *et al.*, 2005). The vented fluxes are recorded by the EC system and consequently carbon storage has no real effect on the long-term carbon budget (Grace *et al.*, 1996). On a daily and annual basis the storage of CO₂ under an EC system averages near zero, so errors in its evaluation are not critical and no correction factors are needed (Greco and Baldocchi, 1996; Anthoni *et al.*, 1999; Baldocchi *et al.*, 2000). Generally, the storage term is very small over short crops and is only an important factor over taller forests.

Advection is when gravity causes the vertical flow of CO₂ from the top of vegetation towards the soil and horizontal movement of CO₂ along a downward gradient (Feigenwinter *et al.*, 2004). Only small slopes are needed to trigger advection (Lee, 1998).

For this reason, flat sites are considered ideal for EC measurements. Worthy of note is the fact that if CO₂ leaves a site by advection, contrary to storage, it is lost to the EC system (Aubinet *et al.*, 2003). Therefore, if night-time fluxes are affected by advection they need to be corrected. An inability to conclusively account for advection is a significant source of uncertainty in EC measurements (Wang *et al.*, 2005). Studies have shown that under some circumstances advection can be of the same magnitude as NEE values (Aubinet *et al.*, 2003; 2005; Feigenwinter *et al.*, 2004); hence, it is essential that measurements made under very stable conditions are rejected to avoid possible significant errors in NEE estimates (Wang *et al.*, 2005; Gu *et al.*, 2005). The rejected data are usually replaced with data derived from a function of temperature parameterised with measurements made during windy conditions (Falge *et al.*, 2001; Wohlfahrt *et al.*, 2005). Some studies have attempted to measure night-time horizontal advection in different ecosystems (Aubinet *et al.*, 2003; Staebler and Fitzjarrald, 2004; Feigenwinter *et al.*, 2004). However, the underlying theories and methodologies are still under debate and require some refinement before being widely accepted (Aubinet *et al.*, 2003; Finnigan and Raupach, 2003). Other authors do not consider advection to be a critical factor in EC (Pilegaard *et al.*, 2001).

3.2.5: EC Tower and Sensor Considerations:

EC sensors and auxiliary equipment are usually mounted on a scaffold tower. The positioning of this tower can severely alter air flow and so must be given some consideration. The tower location must allow for the sampling of representative fluxes from the area of interest but bulky structures can break up large eddies, so the tower must be stream-lined to avoid obstructing the air flow or shadowing the sensors from the wind (Kaimal and Finnigan, 1994; Aubinet *et al.*, 2003). To minimise interference sensors must be placed several metres upwind or on top of the tower (Baldocchi *et al.*, 1996). Most researchers achieve this by placing the sensors on a boom, which overhangs the main body of the scaffolding.

When considering the optimal position of equipment it is vital to understand the physics behind air movement and eddy formation. Air flow can be viewed as a horizontal flow of numerous rotating eddies (Burba and Anderson, 2005). Close to the ground, smaller eddies dominate and transfer most to the flux; while higher above the ground, larger eddies prevail and contribute more (Burba and Anderson, 2005). Small eddies rotate at high frequencies and larger ones rotate more slowly. All micro-meteorological measurements are made within the atmospheric boundary layer (ABL) (Lenschow, 1995). ABL is the

lower part of the atmosphere that interacts with the biosphere. The depth of the ABL depends on the amount of mechanical mixing, caused by surface friction, and scalar mixing, caused by thermals rising from warmed surfaces (Moncrieff *et al.*, 2000). If a sensor is located too high it will be outside the ABL and will register fluxes that originated from locations further upwind that are not representative of the vegetation below. If it is located too low it may not register flux transport by smaller eddies (Aubinet *et al.*, 2003; Burba and Anderson, 2005). The lowest placement height of the sensor should be just above the roughness sub-layer (Burba and Anderson, 2005).

The sonic anemometer must be properly levelled and regularly cleaned as the presence of dust and dirt or the build-up of rain droplets or snowfall on the sensor head alters the distance between the transducer and receiver, thereby distorting the wind speed calculation. The sonic anemometer should also be positioned close to the IRGA, usually within 0.5 m, to minimise any flow disturbances between the two systems that can cause flux under-estimation. The IRGA should be mounted with the sensor head vertical or at a slight tilt, to facilitate water run-off and lessen the obstruction to wind over a range of azimuthal directions (LI-COR manual).

In order to account for all the significant eddies that contribute to the turbulent fluxes of CO₂, the atmosphere must be sampled frequently and for a sufficient duration (Baldocchi, 2003; Burba and Anderson, 2005). A sampling frequency of at least ten times a second has proven adequately long to capture all low frequency fluxes (Lenschow, 1995; Moncrieff *et al.*, 2000). It is generally accepted that sampling and averaging over a duration of 30 to 60 minutes is reasonable for successfully accounting for all flux contributions (Massman and Lee, 2002). In practice a 30 minute sampling interval is often employed as studies have shown that this can achieve an overall accuracy of about 10% even in near neutral conditions (Baldocchi *et al.*, 1988; Verma, 1990; Lenschow *et al.*, 1994). A sampling rate of between 10 to 20 Hz is employed to sample the high frequency proportion of the fluxes (Anderson *et al.*, 1984; Moncrieff *et al.*, 1997).

3.2.6: Footprint and Fetch:

The fluxes measured by the EC system are effectively an integration of fluxes from a variety of sources and sinks in the landscape for a distance of several hundred meters upwind from the sampling point (Moncrieff *et al.*, 2000). This area is difficult to define and varies depending on thermal and mechanical turbulence (Long and Hällgren, 1993).

For this reason, a large area of vegetation is required to guarantee that the sampled eddies result from the canopy under investigation, rather than an adjacent site (Kljun *et al.*, 2004). This area is termed the ‘footprint’; a concept pioneered by Schuepp *et al.* (1990) and LeClerc and Thurtell (1990). A footprint is defined as the area upwind of the measurement site contributing to the measured flux (Schuepp *et al.*, 1990). Schmid (2002) describes it as akin to the “field of view” of the measurement of surface atmospheric exchange. It is possible to estimate the extent of the footprint using the roughness length and an assumed logarithmic wind profile. The roughness length describes the influence that aerodynamic resistance of a plant canopy has on turbulent momentum. It is estimated to be approximately 10% of the height of the plant canopy (Oren *et al.*, 2006; Canadell *et al.*, 2000). In practice, it is simpler to have a fetch that is so extensive that the entire footprint must fall within it under prevailing wind conditions.

The size of the flux footprint varies with changes in thermal stability. It increases with measurement height and decreases with surface roughness. The majority of flux contributions arise closer to the sampling point when the atmosphere becomes unstable, with growing stability the fluxes are generated further from the point of measurement (Moncrieff *et al.*, 2000). Studies have shown that, depending on the physical properties of the underlying canopy and atmospheric stability, the extent and shape of the footprint can vary greatly over short periods of time (LeClerc *et al.*, 2003). A convenient rule of thumb suggests a fetch/height ratio of approximately 100:1 (Grelle and Lindroth, 1996). This means that a sensor at a height of 1m above a surface will have a fetch of 100 m. However, during stable conditions and low wind speeds, which generally occur at night, this ratio may increase greatly to 500:1 (Burba and Anderson, 2005). It is also important to consider the area directly surrounding the equipment tower. This area may be a major contributor of fluxes when the measurement height is low, surface roughness is high or if the conditions are very unstable (Burba and Anderson, 2005). For this reason, the vegetation close to the EC tower should be preserved and remain relatively undisturbed. Ideally the site should be flat with an extensive area of uniform vegetation. In practice, natural environments rarely conform to this ideal and often are undulating or gently sloping with a heterogeneous vegetative stand.

3.2.7: Correction Terms, Post-Processing and Gap Filling:

A series of correction terms and post-processing procedures are carried out on EC fluxes. The first correction applied to EC raw data are spike detection. High frequency

instantaneous data will always create occasional spikes due to random electronic noise or physical noise (such as those caused by blockages during precipitation) (Aubinet *et al.*, 2003; Burba and Anderson, 2005). Their detection and removal, termed despiking, can be carried out by custom-made software. Despiking is usually performed by algorithms based on local averaging (Højstrup, 1993) whereby signals above a certain multiple of the standard deviation of a given averaging period are removed. In this way any outliers are considered spikes and are rejected.

Eddy covariance estimates the turbulence fluxes of mass and energy to and from an area. It is important to quantify estimates of uncertainty within the technique. Energy balance closure is used as an independent method to assess the reliability of the EC measurements (Aires *et al.*, 2008; Wilson *et al.*, 2002). Energy balance closure is based on the law of conservation of energy; whereby, the sum of turbulent energy should balance that of available energy. Where the sum of the turbulent heat fluxes (sensible heat (H) and latent heat (λE)) equals the sum of available energy (net radiation (R_n) minus soil heat flux (G)) within the ecosystem, the EC flux data are assumed to be of good quality (Pingintha *et al.*, 2010).

$$Closure = \frac{H + \lambda E}{R_n - G}$$

Complete closure would yield a value of 1. In practice, there is always an imbalance between the EC fluxes and the available energy (Hipps *et al.*, 2006); Wilson *et al.* (2002) reviewed the FLUXNET sites and reported an average of 80% for energy balance closure. It is generally regarded that the eddy-covariance method systematically underestimates turbulence fluxes (Foken *et al.*, 2006); a comprehensive review of the possible reasons for this disagreement has been published (Culf *et al.*, 2004). One possible factor is errors made in available energy measurements, although improvements in sensors and more stringent data quality tests have reduced the importance of this factor (Foken *et al.*, 2006). Energy storage within the canopy and soil may also be connected to the lack of closure of the energy balance. Meyers and Hollinger (2004) reported that including the heat storage between the measurement level and the ground level as well as the ground heat storage above the soil plate helped balance closure in maize and soybean crops by 3% and 6% respectively. A further possible reason for the imbalance between turbulent and available energy may relate to the different scales of measurement in R_n and G compared H and λE (Wilson *et al.*, 2002; Schmid, 1994). The EC measurements represent a large and

fluctuating area while the net radiometer and soil heat flux plate measure from a relatively small portion of the flux footprint (Pingintha *et al.*, 2010). Despite these drawbacks, energy balance closure is often included in published studies as a guide in identifying non-vertical turbulent fluxes.

EC fluxes are subjected to a series of tests to eliminate data that fail certain criteria. Fluxes must be corrected for latent heat, lateral momentum (Schotanus *et al.*, 1983), high frequency losses (Moore, 1986, Leuning and Judd, 1996; Moncrieff *et al.*, 1997) and air density corrections (Webb *et al.*, 1980). It is also necessary to perform co-ordination rotation calculations on the orthogonal wind vectors (w , u , and v) in order to correct for any instrument misalignment and non-level terrain (Baldocchi *et al.*, 2003). This means the vertical velocity, w , is rotated to zero to allow flux covariances to be computed orthogonal to the mean stream-line (Lee *et al.*, 2004). The aim is to eliminate errors caused by sensor tilt relative to the underlying terrain or aerodynamic shadowing due to the sensor or tower (Aubinet *et al.*, 2003). Regularly, the density of CO₂, rather than its mixing ratio is measured by the EC system. Webb *et al.* (1980) predicted that such fluxes must then be corrected for density fluctuations induced by concurrent fluxes of latent and sensible heat (termed Webb, Pearman and Leuning (WPL) corrections). The simultaneous transfer of sensible and latent heat causes fluctuations in air density, these fluctuations can erroneously be attributed to fluctuations in CO₂ density by the IRGA. Leuning *et al.* (1982) confirmed this prediction experimentally. Before making any comparisons between different sites, it is necessary to ensure the fluxes were computed and processed in the same way (Aubinet *et al.*, 2003). A major aim of FLUXNET is to standardise post-processing from all the network contributors.

Gaps in a continuous data stream are inevitable. Gaps in EC data can mainly be attributed to periods of system and sensor malfunctioning, downtime for calibrations or maintenance, and when there are spikes in the raw data (Baldocchi *et al.*, 1996). Gaps can also be generated during activities such as harvesting or planting. The rejection of data also creates gaps. Data are rejected when stationarity tests or integral turbulence characteristics fail; when the flux footprint extends outside the study site; or when heavy precipitation reduces the optimal performance of the open-path sensor. The removal of 'bad' data is an important process in quality control as it ensures that results do not have a bias (Burba and Anderson, 2005). Data removal is intrinsically site- and instrument-specific. FLUXNET data centre state that the average data coverage is between 65% and 75%, while Falge *et al.*

(2001) found that rejecting up to 40% of data produces repeatable annual sums due to the adequate size of the statistical population.

There are a number of different gap-filling techniques that have been developed independently for site-specific projects (Falge *et al.*, 2001; Moffat *et al.*, 2007). The techniques are based on a wide range of approaches, including interpolation, probabilistic filling, look-up tables, non-linear regression, artificial neural networks and process-based models (Falge *et al.*, 2001; Barr *et al.*, 2004; Hollinger, 2004; Gove and Hollinger, 2006). Gap-filling techniques have been reviewed and the results suggest that most practices yield very similar values (Falge *et al.*, 2001). The effect of the different gap-filling methods on the annual sums of NEE are modest, with most falling within a range of $\pm 25 \text{ g C m}^{-2} \text{ yr}^{-1}$ (Moffat *et al.*, 2007). Hence, the practice of filling missing data itself does not produce a significant source of bias error. However, it should be stated that long data gaps are more difficult to fill; gaps that span days to weeks carry increasing uncertainty because the underlying properties of the ecosystem may have changed over the time period (Richardson and Hollinger, 2007). Similarly, day and night-time data often need to be gap-filled separately as they are subject to empirical relationships that may not remain valid over a twenty-four hour period.

3.2.8: Aims:

The aim of this study was to measure the ecosystem CO_2 exchanges over a *Miscanthus x giganteus* stand in Oak Park Research Centre, during two years of continuous measurements. The ultimate goal was to determine the contribution that *Miscanthus* makes to carbon cycling in an Irish situation and to examine its potential as a carbon sink as well as its potential to offset carbon emissions as a biofuel.

3.3: Methodology:

3.3.1: EC Tower and Instruments:

The EC system was housed on a tubular steel scaffolding tower. The tower was erected during the summer of 2006. It consisted of four galvanised steel uprights (each 3 m in height) that supported two horizontal platforms at heights of 1.5 m and 2.5 m respectively. The lower platform was used to support batteries, a wind turbine voltage regulator and a data logger. This equipment was stored under plastic boxes for waterproofing. Storage at a height was needed to prevent rodents gnawing the electrical cables. The upper platform was used for access to the EC and meteorological sensors. In addition, two small solar panels were positioned here for optimal solar input. Each corner of the tower was set in 30 cm of concrete for structural support. Prior to placing the scaffolding tower the dominant wind speed and direction were determined through discussions with Teagasc staff and a short-term monitoring campaign using a R.M. Young wind vane (Campbell Scientific Ltd, Leicestershire, England). This knowledge was then used to determine the prime location for the tower whereby the majority of fluxes originated within the homogenous stretch of *Miscanthus* plants.

A steel boom was clamped horizontally to the tower off which the EC system was suspended. The boom was raised and lowered over the growing season to maintain a distance of 1.5 m between the equipment and the tallest *Miscanthus* plant within the immediate vegetation surrounding the tower. The EC system consisted of a three-dimensional sonic anemometer (model CSAT-3, Campbell Scientific Ltd, Leicestershire, England) and an open path IRGA (model LI 7500, LI-COR Inc., Lincoln, Nebraska, USA). Air temperature and relative humidity measurements were made with a HMP45C Vaisala temperature and relative humidity probe (Campbell Scientific Ltd, Leicestershire, England); photosynthetic photon flux density was measured with a SKP215 Quantum Sensor (Skye Instruments, Powys, Wales); net radiation was measured using a NR Lite Net Radiometer (Kipp and Zonen, Delft, The Netherlands); wind direction was measured using a R.M. Young Wind Monitor (Campbell Scientific Ltd, Leicestershire, England); soil heat flux was measured using Thermometers HFP01 Soil Heat Flux Plates placed at depths of 2, 10 and 20 cm (Campbell Scientific Ltd, Leicestershire, England). The flux data were collected at a 10 Hz sampling rate, block averaged into 30 minute intervals using the custom written software EdiSol (University of Edinburgh) and stored on a datalogger (CR23X Campbell Scientific Ltd, Leicestershire, England). The climatic data were also

averaged over 30 minutes. Rainfall data were provided by Mr. John Finnan from a meteorological station located within a mile from the *Miscanthus* stand.

Powering the EC system was difficult due to a lack of mains power. Two banks of car batteries, each comprising of three lead acid 12 V 40 AH car batteries were used. A battery bank depleted every three days and needed to be replaced by a fully charged set. Additional energy sources were sought over the duration of the experiment, to reduce the frequency of battery changes. Initially, two small 12 V 250 mAH solar panels were added to the system. Their input was minimal. A Rutland 913 Wind Turbine, which had a maximum output of 20 AH at 12 volts was installed. The turbine was positioned behind the EC tower to avoid any flow disturbances. Finally, two large boat batteries, 12 V 144 AH, were used to increase power supply to the system.

3.3.2: Analysis of the Eddy Covariance Data:

The real time EC data were collected at a 10 Hz sampling rate. The CR23X datalogger had insufficient capacity to store all the raw data; instead, the raw data were temporarily stored in the short-term logger memory and block averaged into 30-minute intervals. The flux data were corrected for variations in air density due to fluctuations in water vapour and heat fluxes using the Webb, Pearman and Leuning correction (Webb *et al.*, 1980). The wind velocity components were rotated into a planar fit coordinate system (Wilczak *et al.*, 2001). Finally, the turbulent fluxes of momentum, sensible heat, latent heat and CO₂ were calculated. The EC and corresponding meteorological data were downloaded manually in the field every week onto a laptop computer. The data were then segregated into weekly data blocks and at the end of each month a data block was created containing a data stream of 30 or 31 days in 30-minute intervals. In this format the data were ready to be analysed.

To ensure only valid EC measurements were examined a series of site-specific criteria were enforced. The flux data were tested to ensure stationarity criteria were met. In this study friction velocity (u^*) thresholds were determined on a weekly basis and were used to distinguish between stable and well-mixed conditions (after Grelle, 1997); whereby, the thresholds were visually determined by examining scatter plots of nighttime fluxes versus u^* . The thresholds were assumed to be located where the fluxes began to level off as u^* increases. Typical threshold values ranged between 0.3-0.4 m s⁻¹. Implementing this approach is not without criticism, as the threshold determination is subjective, nevertheless, the technique is regularly employed (Massman and Lee, 2002). It is also

argued that determining u^* thresholds for fluxes on a regular basis is better than employing a single threshold value for the entire data set, which may create biases as there is no evidence that u^* thresholds would remain constant over time (Gu *et al.*, 2005). Data recorded during calm conditions were rejected, as they do not fully describe the transport of fluxes within the boundary layer.

Flux footprint analysis was carried out on the weekly flux data blocks and any data originating from outside the *Miscanthus* stand was rejected. SCADIS AIRFLOW Editor and SCADIS FOOTPRINT (Sogachev *et al.*, 2002; 2005) were the flux footprint software employed in this study. SCADIS (scalar distribution) was critically evaluated by Vesala *et al.* (2007). AIRFLOW Editor was used to describe the underlying vegetation at the time of EC measurements, FOOTPRINT used this information in conjunction with wind conditions to carry out footprint analysis. The input data was site and time specific. The data required were (a) roughness parameter of the ground (z_0), (b) height of the vegetation above the ground, (c) projection of LAI, and (d) wind speed and direction. With AIRFLOW Editor it was possible to construct a model of the experimental site with grid cells assigned to different surface types, to represent heterotrophic vegetation. In this study, the vegetation was assumed to be homogeneous. However, as analysis was carried out on a weekly basis the rapid change in *Miscanthus* canopy structure over the growing season was accounted for. Where possible, the plant height and LAI data reported in Chapter 2 were used as the input data for AIRFLOW Editor. When weekly biometric data were not collected as part of a continuing experiment, ten spot measurements were made close to the eddy covariance tower. In both cases the data were averaged and the mean values were input into the footprint calculation. The roughness parameter of the ground was assumed to be one-tenth of the average height of the *Miscanthus* stand (Johansson, 2003). The height of the IRGA was kept at a constant distance above the canopy (1 m) through the regular movement of the sensor during the growing season. The wind conditions (speed and direction) were the predominant drivers in determining the size and fetch of the flux footprint. Due to the siting of the EC tower, based on the prevailing wind direction, the majority of the footprint peak ranges were within the *Miscanthus* field. Any fluxes measured when the wind direction was northerly or north-westerly were rejected as they represented fluxes originating from the surrounding vegetation outside the *Miscanthus* stand. Northerly and north-westerly winds accounted for < 4% and 6% of the recorded data respectively.

The data were divided into day and night-time periods. The day and night intervals were defined by photosynthetically active radiation (PAR). Any data points associated with a PAR value greater than $100 \mu\text{mol m}^{-2} \text{s}^{-1}$ were allocated as day-time data, while any data with a PAR value less than $100 \mu\text{mol m}^{-2} \text{s}^{-1}$ were allocated as night-time data. Data collection began on the August 11th 2006 and ceased on the August 10th 2008. For convenience in analysis the data were split into two blocks: Year 1 (August 11th 2006 to August 10th 2007) and Year 2 (August 11th 2007 to the August 10th 2008). Within each year the data were sub-divided into four categories based on the life cycle of the *Miscanthus* plant: Maximum Growth (August to October), Senescence (November to December), Litter Fall (January to April) and Early Growth (May to July).

Day-time gaps were filled using the Michaelis-Menten approach (Michaelis and Menten, 1913) and night-time gaps were filled based on the Lloyd-Taylor equation. (Lloyd and Taylor, 1994). A variety of other gap filling techniques were tested on the EC data. The asymptotic exponential equation of Prioul and Chartier (1977) and the net photosynthetic model of Olsson and Leverenz (1994) were tested on day-time data but the Michaelis-Menten method produced more robust modelled values. The Mean Diurnal Variation (MDV) gap filling strategy (after Falge *et al.*, 2001) was tested on the night-time data. The results were comparable with the results from the Lloyd and Taylor equation approach.

Day-time half hourly data was filled using a rectangular hyperbolic function that describes the response of NEE to PAR (after Michaelis and Menten, 1913):

$$\text{NEE} = \frac{\alpha \cdot \text{PAR} \cdot \text{NEE}_{\text{sat}}}{\alpha \cdot \text{PAR} + \text{NEE}_{\text{sat}}} - R_{\text{eco}}$$

where α is apparent quantum yield ($\mu\text{mol CO}_2 \mu\text{mol}^{-1}$ photons), NEE_{sat} is the saturation value of NEE at an infinite light level and R_{eco} is ecosystem respiration in daytime conditions. As *Miscanthus* is a fast growing plant, the functional response of NEE to PAR was determined separately for each month to account for the different growing stages of the crop. The data were also separated into temperature classes (0-5 °C, 5-10 °C, 10-15 °C etc.) to take account of any effects of temperature on day-time fluxes.

Night-time data gaps were filled using an Arrhenius type temperature function to predicted ecosystem respiration after the Lloyd-Taylor equation (Lloyd and Taylor, 1994):

$$R_{eco} = R_{10} \times e^{\left(E_0 \left(\frac{1}{T_{ref} - T_0} - \frac{1}{T_k - T_0} \right) \right)}$$

where R_{10} is the respiration rate at 10 °C; E_0 describes the temperature dependence of the respiration and is set at 309 K; T_{ref} and T_0 are set at 283.15K and 227.13K respectively (Falge *et al.*, 2001; Lindroth *et al.*, 2008). T_k is temperature in K. Lloyd and Taylor (1994) found a set of E_0 and T_0 values generally applicable for an extensive data set of soil respiration from various ecosystems. In this study the same co-efficients as were found by Lloyd and Taylor (1994) were employed, leaving only the R_{10} as a filtering parameter. For each growth period of the *Miscanthus* life cycle the R_{10} parameterisations were derived from the respective data subset using the computer software ‘Excel Solver’ (Table 3.1).

Table 3.1: R_{10} values derived for each growth period in the life cycle of the *Miscanthus* stand from August 11th 2006 to August 10th 2008.

Year	Growth Period	R_{10} ($\mu\text{mol m}^{-2} \text{s}^{-1}$)
2006	Maximum Growth	2.34 ± 0.02
	Senescence	1.57 ± 0.08
2007	Litter Fall	1.98 ± 0.11
	Early Growth	2.87 ± 0.14
	Maximum Growth	3.51 ± 0.07
	Senescence	1.54 ± 0.10
2008	Litter Fall	2.00 ± 0.04
	Early Growth	2.29 ± 0.03
	Maximum Growth	2.87 ± 0.33

Both the Michaelis-Menten and Lloyd and Taylor models use meteorological variables, PAR and air or soil temperature. Where PAR and temperature data were missing the MDV gap filling strategy was adopted (after Falge *et al.*, 2001). A data window of 14 days in length was created on either side of a gap in the data. The average value for each 30-minute period in a day was estimated to form an average diurnal pattern of the missing parameter. This was then used to fill the original gaps.

After gap filling a continuous data stream of two calendar years was created. An estimation of the total carbon flux (NEE) was made for each week and month by summing together the 7 and 30/31 day data streams. The fluxes were then converted from $\mu\text{mol CO}_2 \text{ m}^{-2} \text{s}^{-1}$ into g C m^{-2} . The monthly estimates of carbon fluxes were combined to produce an annual

carbon flux estimate. Gross primary production (GPP) fluxes were derived from the following equation:

$$NEE = GPP - R_{eco}$$

where R_{eco} (Ecosystem respiration) was assumed to be equivalent to night-time fluxes.

3.4: Results:

3.4.1: Meteorological Data:

The meteorological data were collected from sensors attached to, or surrounding, the EC tower, with the exception of rainfall data, which was kindly supplied by Mr. John Finnan. The meteorological data were averaged over thirty minutes and then expressed on a weekly and monthly basis. PAR, rainfall, soil and air temperatures are important factors in crop development, photosynthesis and respiration; therefore, the monthly averages of these variables are presented in Figures 3.1 to 3.4.

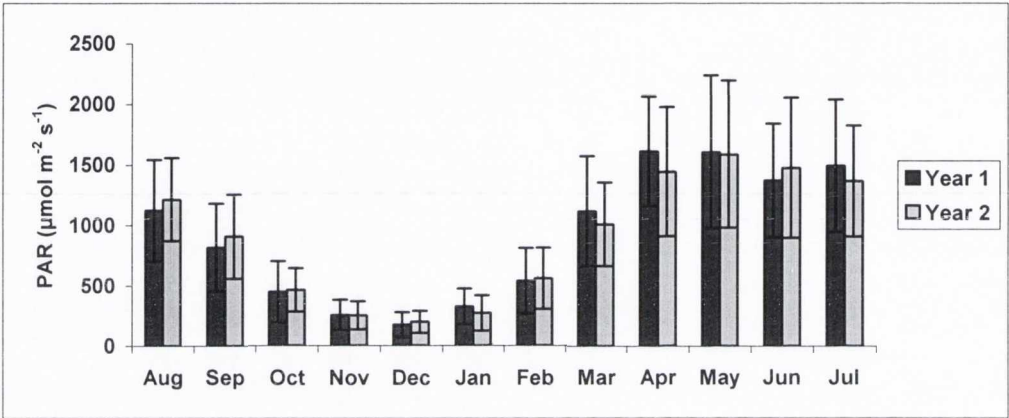


Figure 3.1: Monthly average PAR ($\mu\text{mol m}^{-2} \text{s}^{-1}$) measurements in Years 1 and 2. Year 1 relates to the period August 11th 2006 to August 10th 2007. Year 2 relates to the period August 11th 2007 to August 10th 2008. Measurements were made over a *Miscanthus* stand. Error bars are $\pm$ standard deviation.

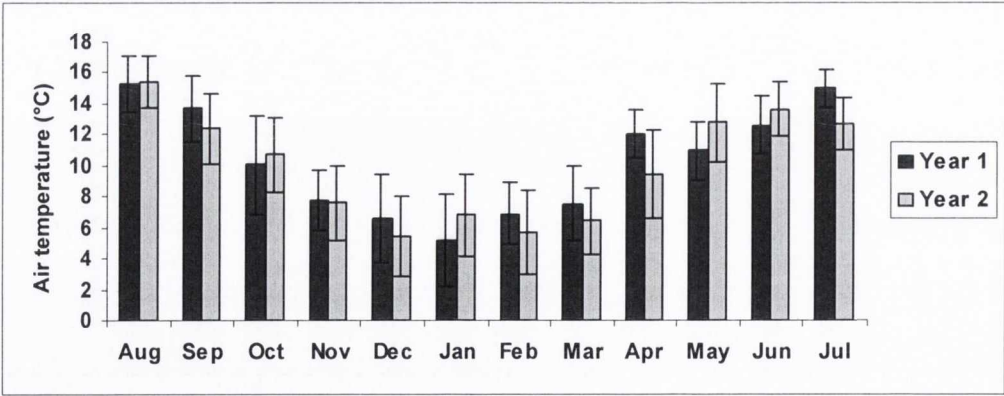


Figure 3.2: Monthly average air temperatures ($^{\circ}\text{C}$) in Years 1 and 2. Year 1 relates to the period August 11th 2006 to August 10th 2007. Year 2 relates to the period August 11th 2007 to August 10th 2008. Measurements were made over a *Miscanthus* stand. Error bars are $\pm$ standard deviation.

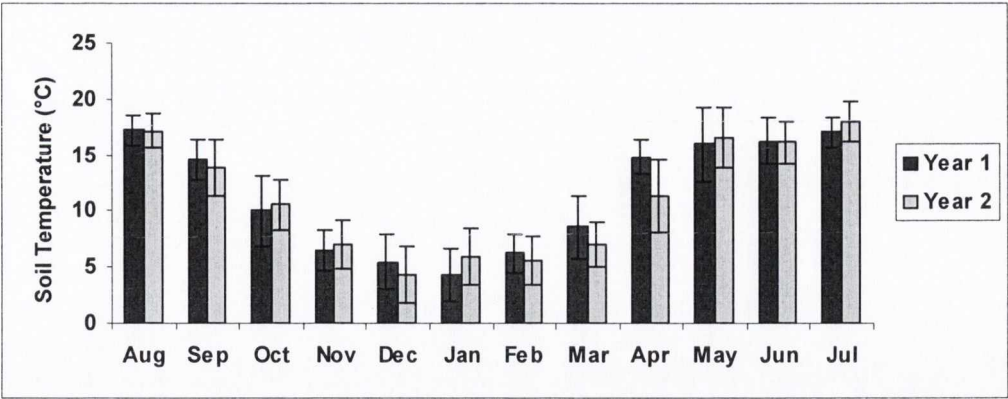


Figure 3.3: Monthly average soil temperatures (°C) in Years 1 and 2. Year 1 relates to the period August 11th 2006 to August 10th 2007. Year 2 relates to the period August 11th 2007 to August 10th 2008. Measurements were made at a depth of 5 cm within a *Miscanthus* stand. Error bars are $\pm$ standard deviation.

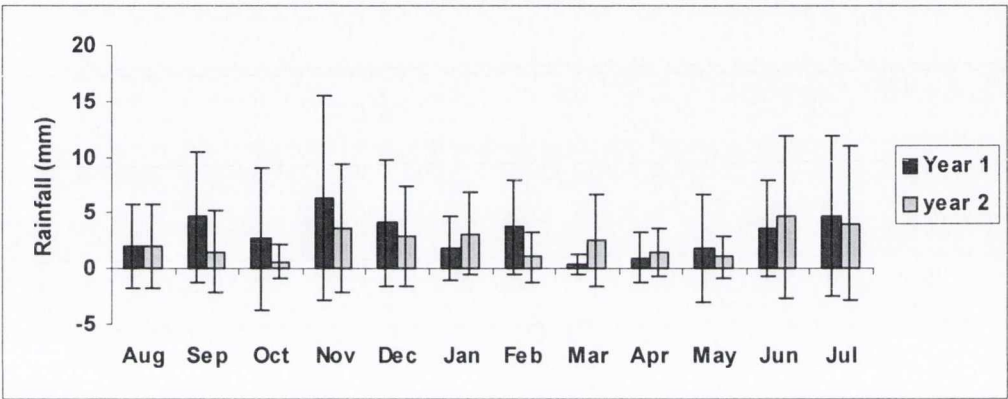


Figure 3.4: Monthly average rainfall measurements (mm) in Years 1 and 2. Year 1 relates to the period August 11th 2006 to August 10th 2007. Year 2 relates to the period August 11th 2007 to August 10th 2008. Measurements were made at a Met. Station close to the *Miscanthus* stand. Error bars are $\pm$ standard deviation.

Diurnal patterns in PAR and air temperature were observed. PAR fluxes showed an increase from day break (approximately 06.00 hours in summer months and 08.00 hours in winter months) to peak fluxes at approximately 13.00 hours then decreasing through the afternoon to dusk (approximately 21.00 hours in summer months and 17.00 hours in winter months). Air temperatures were relatively stable in the early hours of the morning (00:00 hours to 06:00 hours in summer months and 00:00 hours to 08:00 hours in winter months). After sunrise air temperatures steadily increased until approximately 13:00 hours, where it remained high in summer, then tended to decrease rapidly after 15:00 hours in winter and 19:00 hours in summer. Soil temperatures were relatively stable on a twenty-four hour basis. Rainfall events were irregular. Year 1 experienced higher PAR, air and soil temperatures, and rainfall compared to Year 2 (Table 3.2)

Table 3.2: Annual average and cumulative values of meteorological measurements for Years 1 and 2. Year 1 relates to the period August 11th 2006 to August 10th 2007. Year 2 relates to the period August 11th 2007 to August 10th 2008. Measurements were made over a *Miscanthus* stand.

Measurement	Year 1		Year 2	
	Average	Cumulative	Average	Cumulative
PAR ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	904.7	329317	898.8	328961
Air Temperature ($^{\circ}\text{C}$)	10.3	3781.5	9.8	3618.9
Soil Temperature ($^{\circ}\text{C}$)	11.3	4131	11.1	4059

*Average daily rainfall

3.4.2: Eddy Covariance:

3.4.2.1: Energy Closure:

In this study the energy balance closure was tested using a linear regression between the sum of sensible and latent heat fluxes (H and λE) and the amount of available energy ($R_n - G$). Half-hourly data collected from the entire period of the experiment were analysed. Figure 4.5 shows the relationship between turbulent and available energy fluxes over the *Miscanthus* stand in Oak Park, from August 2006 to August 2008, with the following equation:

$$(H + \lambda E) = 0.77(R_n - G) + 7.74$$

Figure 3.5 suggests that the EC measurements underestimated the turbulent fluxes by 23% ($R^2 = 0.77$). The degree of energy balance closure is not perfect but does show a good agreement between turbulent and available fluxes. There was a larger degree of scatter in the upper flux range ($>400 \text{ W m}^{-2}$), a phenomenon often seen in the literature. The *Miscanthus* site values compare favourably with those reported by Wilson *et al.* (2002) from 22 FLUXNET sites where slopes, intercepts and R^2 values ranged between 0.53 and 0.99, -32.9 and 36.9 W m^{-2} and 0.64 and 0.34 respectively. The good balance closure at the *Miscanthus* site does not fully accredit the EC data set; however, it does provide a good indication that the site is not subject to major advection.

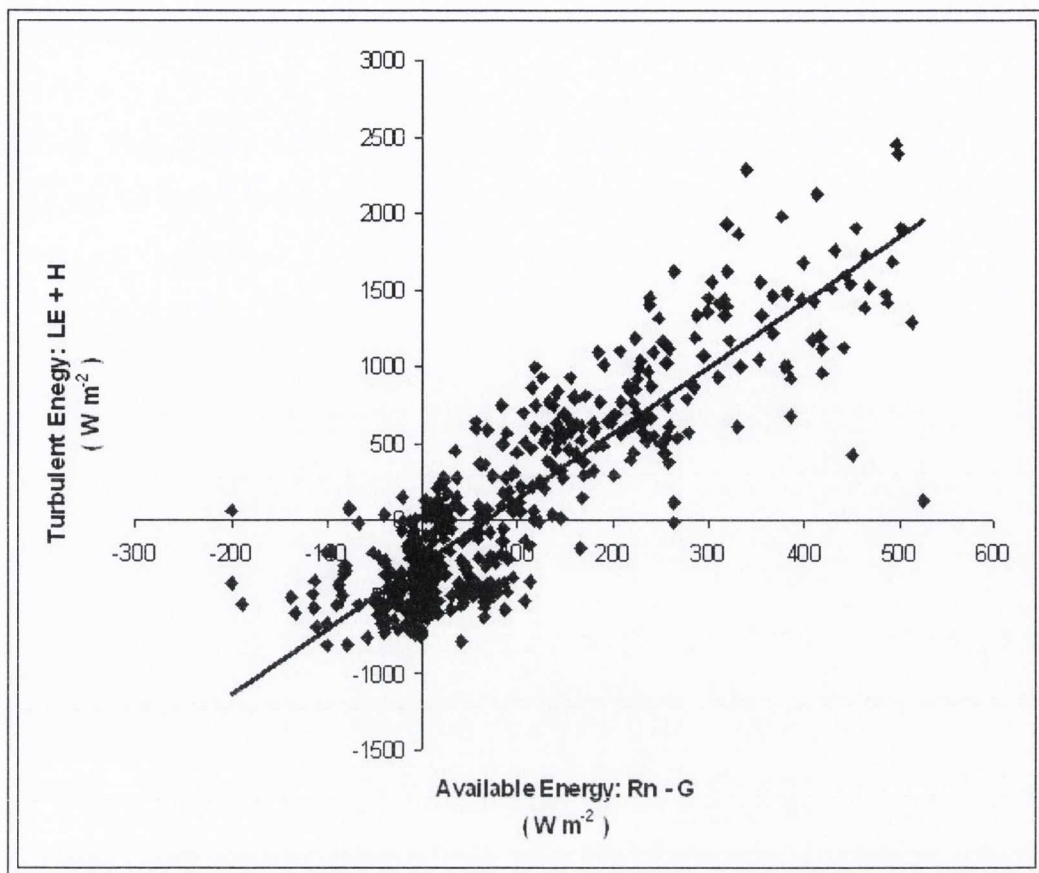


Figure 3.5: Relationship between turbulent and available energy, over a homogenous *Miscanthus x giganteus* canopy at Oak Park Research Centre, Co. Carlow. Data collected between 11th August 2006 and the 10th August 2008. (Slope = 0.77, $R^2=0.77$).

3.4.2.2: Gap Filling and Modelling:

The EC system over the *Miscanthus* stand was run for 24 months, from August 2006 to August 2008. Ideally, a continuous data stream should be generated from this time period but small data gaps were generated due to difficulties maintaining battery power at the site, data rejection during processing and analysis, and downtime during calibration and maintenance. Larger gaps were created due to equipment failure and weather preventing access to the site. Gaps of over a week occurred between the following dates: 2006: October 2nd-17th, December 6th-14th; 2007: February 20th-March 4th, March 17th-31st, July 13th-24th; 2008: January 21st-31st, Jul 17th-25th. Over the duration of this project a total of 3382 hours of data were gap filled. This accounted for 19% of the total data stream. Data losses of 25% - 35% have been reported in the literature (Baldocchi *et al.*, 2002; Falge *et al.*, 2001). A gap of 26 hours was the median value for the data set. Modelling such small gaps can be achieved with a high level of accuracy.

Gaps in daytime data (defined as $PAR > 100 \mu\text{mol m}^{-2} \text{s}^{-1}$) were filled using the Michaelis-Menten function that describes the response of NEE to PAR. To investigate how well the

Michaelis-Menton function described the data, an entirely modelled data set was generated then plotted against the corresponding non-gapfilled measured day time data (Figure 3.6). A linear relationship would indicate the modelled data accurately predict the measured values. The modelled data closely resembled the measured fluxes and so the Michaelis-Menton function was employed for daytime gapfilling. The regression co-efficient indicates that PAR accounted for 70% of the variation in NEE.

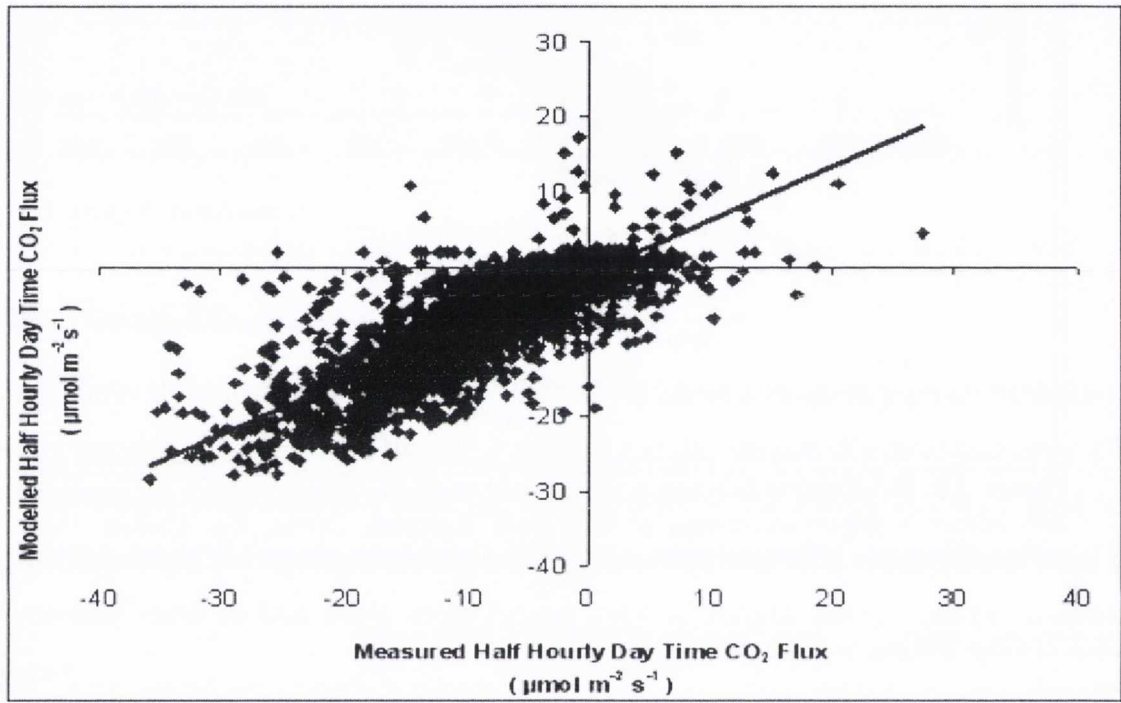


Figure 3.6: Relationship between measured half hourly daytime CO₂ fluxes and modelled half hourly daytime CO₂ fluxes using the Michaelis-Menten equation. Measured data were collected between 11th August 2006 and 10th August 2008 over a homogenous *Miscanthus x giganteus* canopy at Oak Park Research Centre, Co. Carlow. (Slope = 0.71, R² = 0.70).

Gaps in night-time data (defined as PAR < 100 μmol m⁻² s⁻¹) were filled using the Lloyd and Taylor temperature function. Either air or soil temperature can be used. To investigate which temperature type best described the night-time data two modelled data sets were generated for the experimental period based on air and soil temperatures; these were then plotted against the non-gapfilled measured night-time data (Figure 3.7 and 3.8). The simulated data based on air temperature fitted the observed data better (R² = 0.83) than the data modelled on soil temperature (R² = 0.53). Therefore, the Lloyd and Taylor function, as parameterised by air temperature, was used to gap fill night-time data.

The robustness of the day and night-time models were examined by comparing a complete modelled data set (day and night combined) to the actual non-gapfilled measured flux data

for the same period (Figure 3.9). A linear relationship would demonstrate accurately modelled data. A good correlation between the measured and modelled data was demonstrated with 78% of the variation in NEE being accurately described by the modelled data.

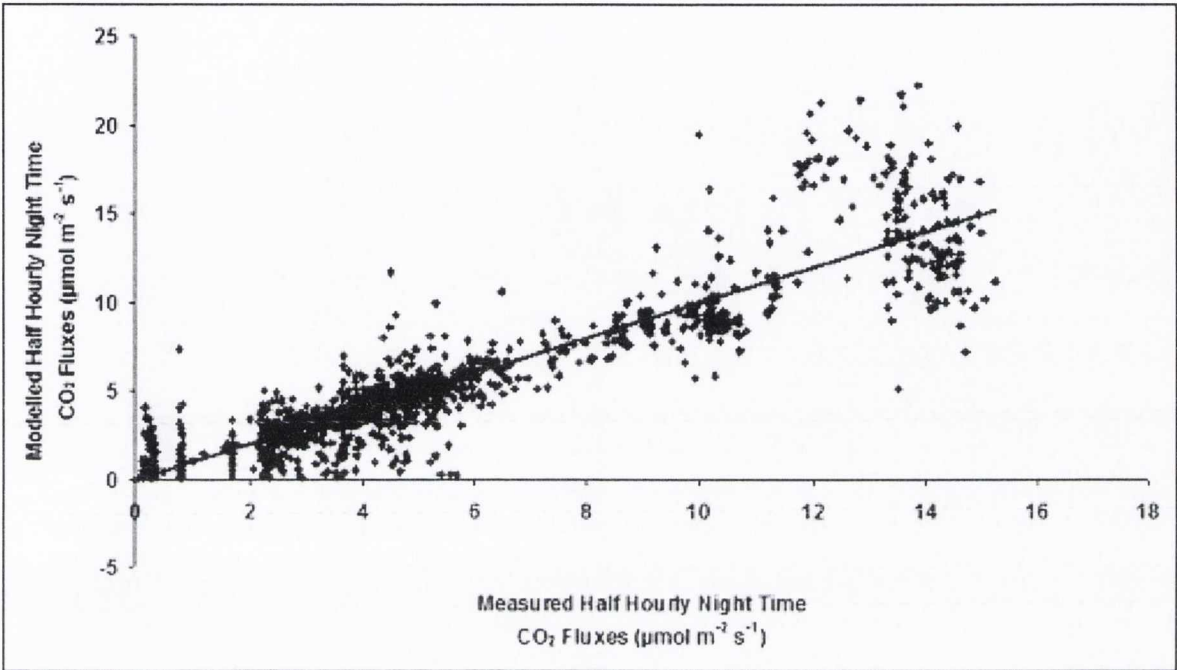


Figure 3.7: Relationship between measured half hourly night-time CO₂ fluxes and modelled half hourly night-time CO₂ fluxes using air temperature and the Lloyd and Taylor function. Measured data was collected between 11th August 2006 and 10th August 2008 over a homogenous *Miscanthus x giganteus* canopy at Oak Park Research Centre, Co. Carlow. (Slope =0.99, R² = 0.83).

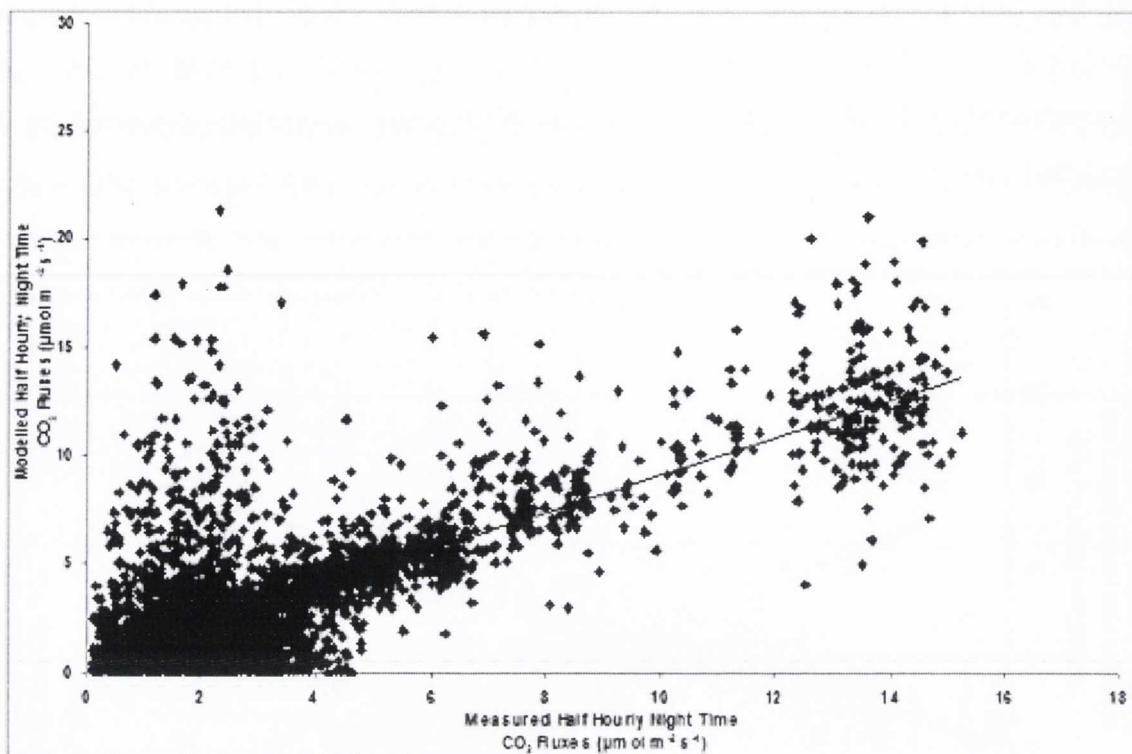


Figure 3.8: Relationship between measured half hourly night-time CO₂ fluxes and modelled half hourly night-time CO₂ fluxes using soil temperature and the Lloyd and Taylor function. Measured data was collected between 11th August 2006 and 10th August 2008 over a homogenous *Miscanthus x giganteus* canopy at Oak Park Research Centre, Co. Carlow. (Slope =0.85, R² = 0.53).

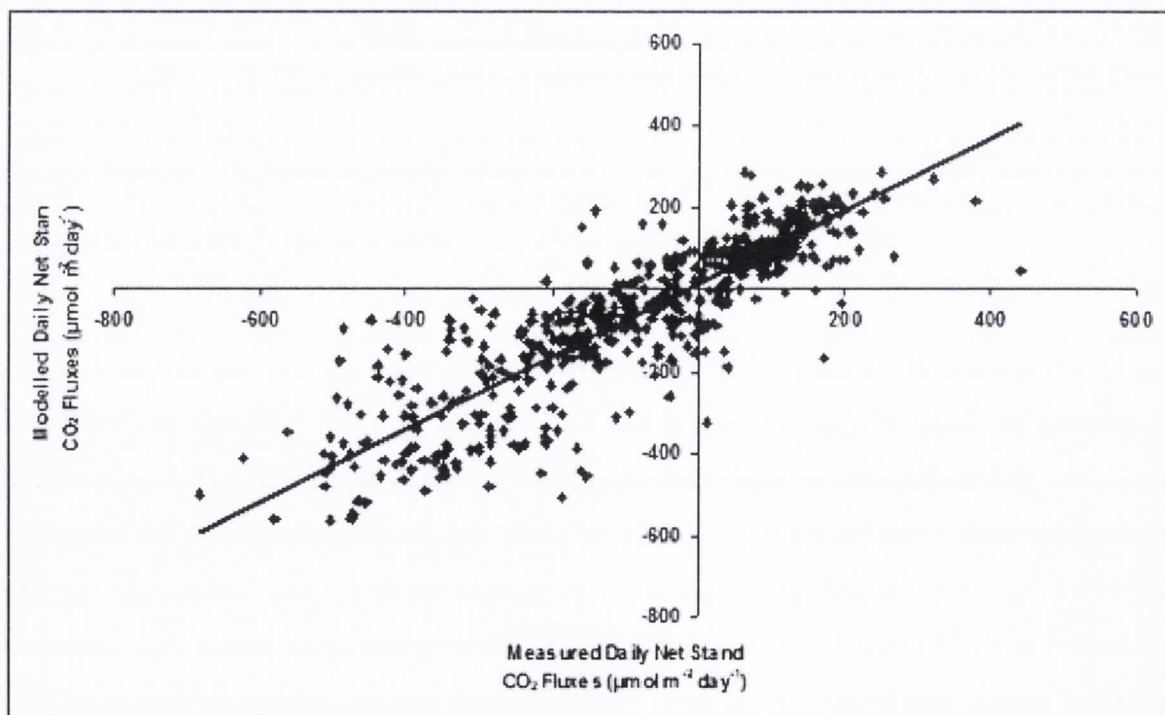


Figure 3.9: Relationship between measured daily net stand CO₂ fluxes and corresponding modelled daily net stand CO₂ fluxes. Modelled data were calculated using the Michaelis-Mention and Lloyd and Taylor functions. Measured data was collected between 11th August 2006 and 10th August 2008 over a homogenous *Miscanthus x giganteus* canopy at Oak Park Research Centre, Co. Carlow. (Slope =0.88, R² = 0.78).

3.4.2.3: Ecosystem Carbon Fluxes:

The Net Ecosystem Exchange (NEE) fluxes of CO₂, as measured by the EC system, for the twenty-four months of this study are shown in Appendices 13 to 36. The positive flux values indicated periods of net ecosystem loss of CO₂, while negative values indicated a net gain of CO₂ by the ecosystem. Figure 3.10 illustrates the NEE fluxes over the *Miscanthus* stand from August 2006 until August 2007 (see Appendix 37 for the Julian Day Calendar). The trends of NEE fluxes over the year can be divided into the four life stages of the *Miscanthus* crop: Maximum Growth (approximately Julian Day 223-304, August to October); Senescence (approximately Julian Day 305-365, November to December); Litter Fall (approximately Julian Day 1-90, January to March); Early Growth (approximately Julian Day 91-222, April to July). In Year 1 (August 11th 2006 to August 10th 2007) during the Maximum Growth period, the daily maximum rates of CO₂ uptake fell within the range of -3 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ to -35 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$. Carbon loss fluxes during this time ranged between 0 to +20 $\mu\text{mol m}^{-2} \text{ s}^{-1}$. In the Senescence period the *Miscanthus* loses its ability to photosynthesise as leaves die back. Within this stage a steady decrease in carbon uptake was observed; the absorption of carbon into the ecosystem is at its lowest during this time of the year. In the Litter Fall period the *Miscanthus* no longer had any photosynthetically active biomass and leaves were shed following the first frost of the winter. During this stage a slow increase in ecosystem carbon uptake from the previous period was observed. *Miscanthus* cannot be responsible for this and so it must be attributed to the development of understory vegetation. The two large data gaps within this period make it difficult to accurately describe trends; however, in general the carbon assimilation increased in magnitude while carbon release showed a slight decline from the previous period. The daily maximum rates of CO₂ release fell to the range +9 to +5 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$. The lower carbon release fluxes are likely to be attributed to a decrease in monthly temperatures. In the final life stage, Early Growth, carbon uptake rates increased dramatically in parallel with the re-emergence and rapid growth of the *Miscanthus*; increasing from a daily maximum carbon uptake of -18 to -40 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ over the four month period. Carbon release increased from the Litter Fall period and fall within a remarkably similar range as the Maximum Growth period. The abundance of fresh litter fall from the previous months combined with warmer temperatures were the most likely driving factors in higher net carbon losses from the ecosystem.

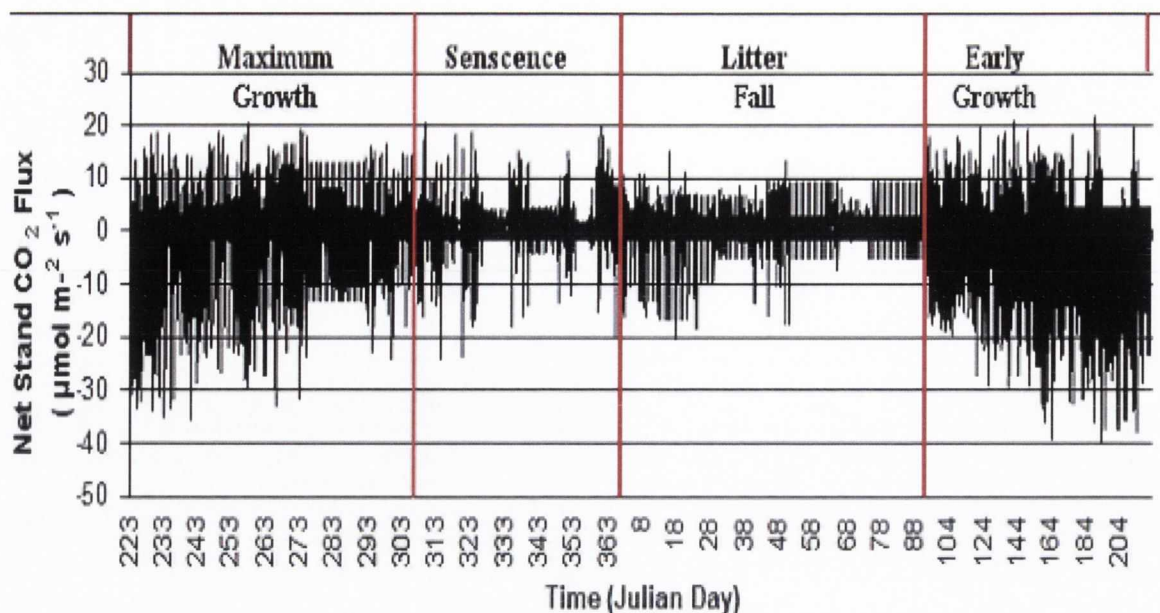


Figure 3.10: Net stand CO₂ flux measured above a homogenous *Miscanthus x giganteus* canopy at Oak Park Research Centre, Co. Carlow. Data collected from 11th August 2006 to 10th August 2007. Negatives values indicate a net gain of CO₂ by the ecosystem; positive values indicate a net loss of CO₂ from the ecosystem.

Figure 3.11 presents the net stand fluxes of CO₂ from *Miscanthus* between August 2007 and August 2008. There was a strong resemblance in the pattern of CO₂ fluxes with those observed in the previous year; although, a greater range of fluxes was seen in the Year 2 (August 11th 2007 to August 10th 2008). There were fewer large data gaps in this measurement period making it easier to decipher trends in the data. In the Maximum Growth period, average daily maximum rates of CO₂ uptake and loss fell within the ranges of -30 to -18 μmol CO₂ m⁻² s⁻¹ and +10 to +15 μmol μmol CO₂ m⁻² s⁻¹ respectively. In the Senescence stage there was a marked decrease in carbon assimilation with average maximum rates at -8 μmol CO₂ m⁻² s⁻¹. Net ecosystem respiration showed a small decrease from the Maximum Growth stage with only two occasions of CO₂ release exceeding +20 μmol CO₂ m⁻² s⁻¹. In the Litter Fall period a steady increase in carbon uptake was observed while maximum R_{eco} fluxes averages ranged between +8 and +15 μmol CO₂ m⁻² s⁻¹. Carbon assimilation continued to increase in the Early Growth stage with a peak rate at -32 μmol CO₂ m⁻² s⁻¹. There was considerable variation in the ecosystem respiration fluxes; the average rates were more similar to those registered in the Maximum Growth stage as opposed to the Senescence or Litter Fall periods.

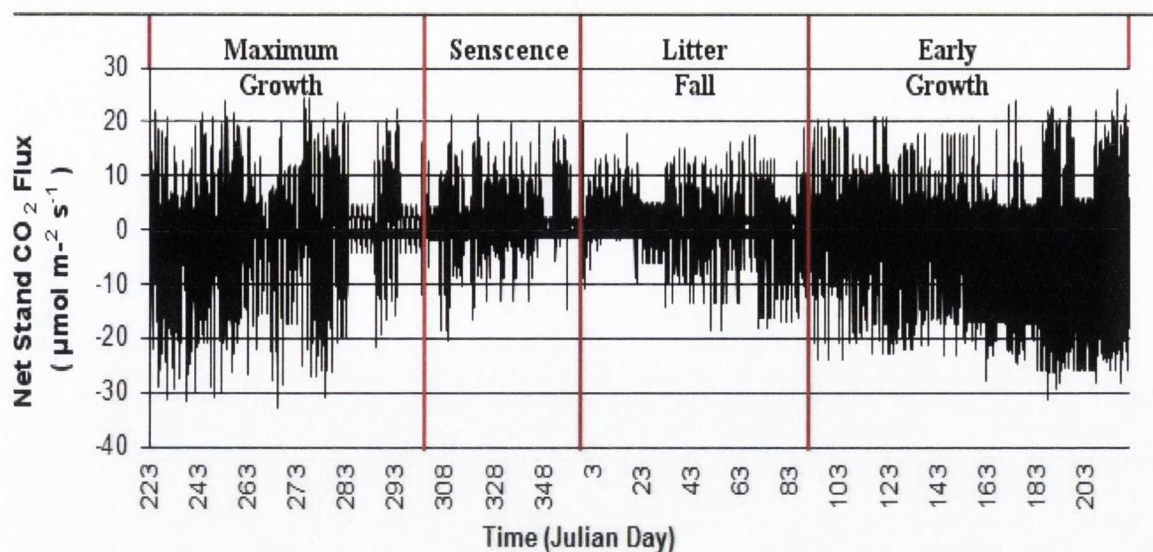


Figure 3.11: Net stand CO₂ flux measured above a homogenous *Miscanthus x giganteus* canopy at Oak Park Research Centre, Co. Carlow. Data collected from 11th August 2007 to 10th August 2008. Negatives values indicate a net gain of CO₂ by the ecosystem; positive values indicate a net loss of CO₂ from the ecosystem

Average diurnal cycles of ecosystem CO₂ fluxes were produced for each life stage of the *Miscanthus* crop (Figures 3.12 (Year 1) and 3.13 (Year 2)) to demonstrate the significant impact of phenology on net ecosystem exchange and carbon sink-source strengths. The Early Growth stage, in Year 1, displayed the highest average rates of both carbon uptake and loss from the stand, ranging from -17 to +7 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$. Within this life stage the *Miscanthus* stand acted as a net source of carbon until shortly after 06.00 hours when it switched to a net sink of CO₂. Maximum carbon uptake occurred at -10 to -15 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ between 08.00 hours and 18.30 hours and was associated with peaks in both air temperature and PAR fluxes. As PAR decreased in the evening, the rates of CO₂ uptake also decreased and the *Miscanthus* stand switched from a net sink to a net source at 19:00 hours. R_{eco} rates increased until 21:00 hours then reached a plateau. The Maximum Growth diurnal followed the same pattern within a smaller range of fluxes: -16 to +4 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$. Here the switch from carbon source to sink occurred later in the day, closer to 08:00 hours and switched back to a carbon source earlier at approximately 18:00 hours. The Senescence and Litter Fall diurnal cycles fell within further reduced ranges of only -4 to +3 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ and -5 to +2 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ respectively. During the Senescence stage the *Miscanthus* stand acted as a weak carbon sink for a short period of time between 09:30 hours and 15:00 hours. The Litter Fall diurnal cycle showed the greatest amount of fluctuation with no discernible trend from 09:00 hours to 14:00 hours; outside these hours the *Miscanthus* stand had low and stable levels of carbon release.

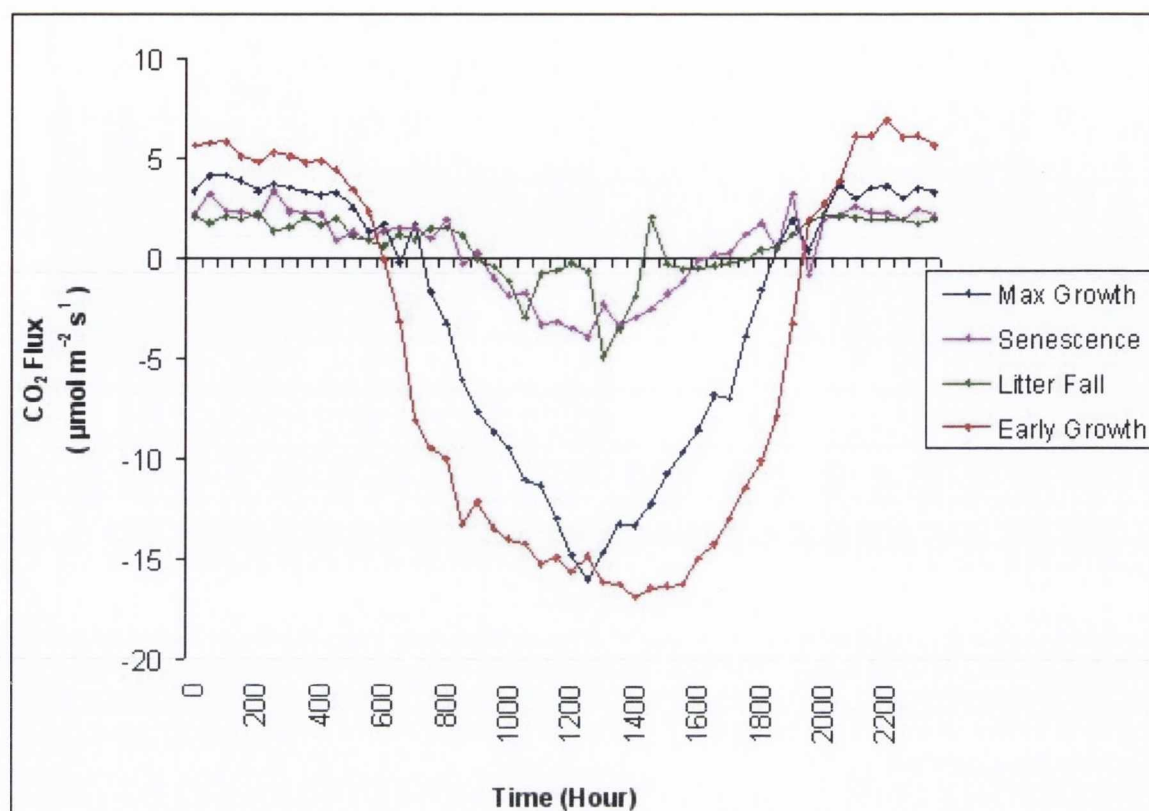


Figure 3.12: Average diurnal cycle of ecosystem CO₂ flux, based on EC data collected from the 11th August 2006 to the 10th August 2007. EC data collected over a homogenous *Miscanthus x giganteus* canopy at Oak Park Research Centre, Co. Carlow. Max Growth period relates to (August, September and October 2006); Senescence relates to (November and December 2006); Litter fall relates to (January, February and March 2007); early growth relates to (April, May, June and July 2007). Positive values indicate net loss of CO₂ from the ecosystem while negative values indicate net uptake of CO₂ by the ecosystem.

In Year 2 (Figure 3.13) maximum peak respiratory losses and photosynthetic gains occurred in the Maximum Growth stage at $+5 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ and $-13 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ respectively. The *Miscanthus* stand switched from a net carbon source to a net sink at 06:30 hours and reverted to a carbon source at 19:00 hours. The range of values in this life stage is comparable to those seen in Year 1. The Early Growth period in Year 2 displayed a much reduced range compare to Year 1 ($-11 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ to $+4 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ against $-17 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ to $+7 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$). The system changed from a net source of carbon to a sink and back again at 06:30 hours and 20:00 hours. The Senescence diurnal cycle in Year 2 was remarkably similar to that of Year 1, with the *Miscanthus* stand acting as a weak carbon sink between 10:00 hours and 15.30 hours. The Litter Fall diurnal showed less variation in Year 2 than in the previous year. Night-time respiratory losses remained relatively constant at $+2 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$, after sunrise these fluxes decreased slowly until 10:00 hours when the system shifted to a net carbon sink. At 17:00 hours net respiration fluxes resumed and levels became steady again at $+2 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$.

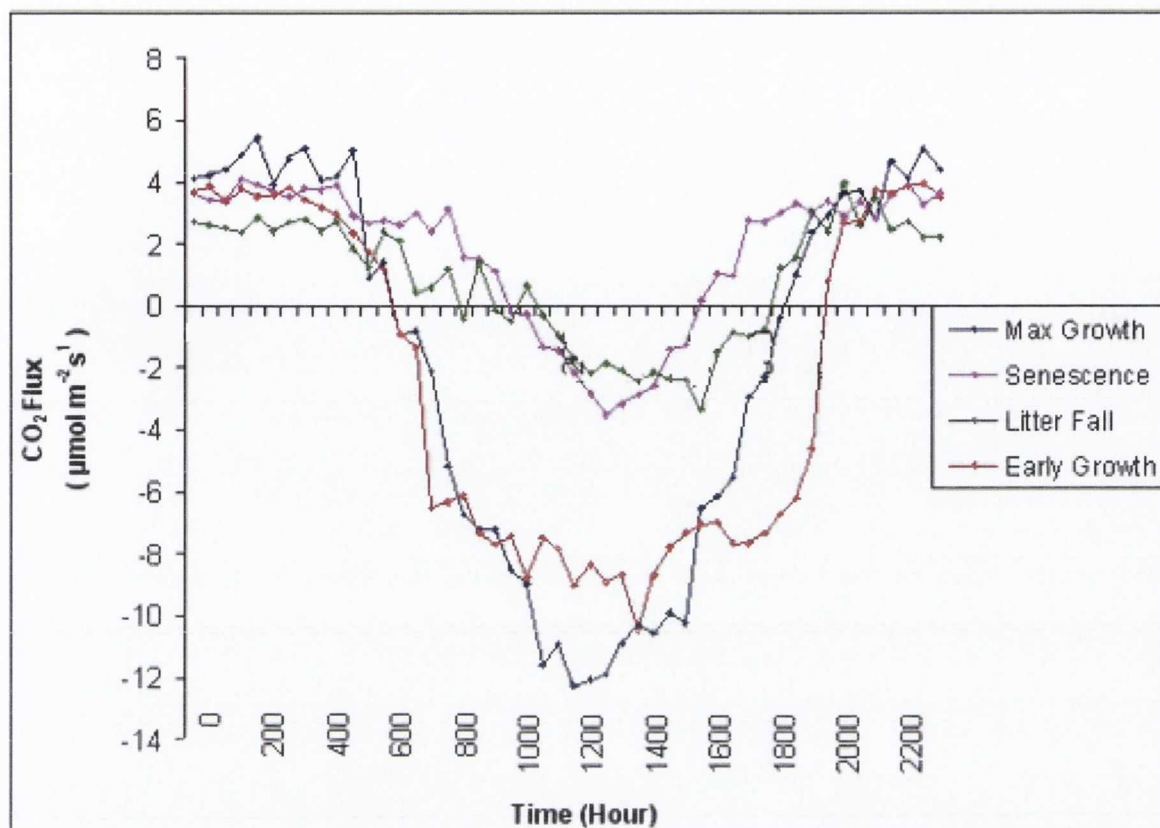


Figure 3.13: Average diurnal cycle of ecosystem CO₂ flux, based on EC data collected from the 11th August 2007 to the 10th August 2008. EC data collected over a homogenous *Miscanthus x giganteus* canopy at Oak Park Research Centre, Co. Carlow. Max Growth period relates to (August, September and October 2007); Senescence relates to (November and December 2007); Litter fall relates to (January, February and March 2008); early growth relates to (April, May, June and July 2008). Positive values indicate net loss of CO₂ from the system while negative values indicate net uptake of CO₂ from the system

The thirty minute flux data were arranged into seven day blocks and summed together to calculate the weekly NEE. This was divided into its component fluxes, GPP and R_{eco}, based on the following equation, where night-time data were assumed to represent R_{eco}:

$$(NEP = GPP - Reco)$$

Average weekly GPP and R_{eco} fluxes were -22.138 g C m⁻² wk⁻¹ and +16.873 g C m⁻² wk⁻¹ in Year 1 and -22.464 g C m⁻² wk⁻¹ and +14.91 g C m⁻² wk⁻¹ in Year 2. From Year 1 the ecosystem was a carbon sink for a total of 30 weeks and a carbon source for 22 weeks; whereas in Year 2 the *Miscanthus* acted as a carbon sink for 25 weeks and a carbon source for 27 weeks.

Cumulative fluxes were also calculated for each of the components of the NEE. The differences in the cumulative fluxes of NEE, GPP and R_{eco} between the two measurement years are shown in Figure 3.14. Year 1 sequestered more carbon, through GPP fluxes

compared to Year 2 in eleven out of the twelve months; it was only the strength of carbon uptake into the stand in the summer of 2008 that brought both years to a similar cumulative GPP flux value for the measurement period ($-53,295 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ for Year 1 and $-54,079 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ for Year 2). Both years had similar cumulative respiration fluxes until the beginning of the fallow period in December; thereafter, Year 1 had higher respiration rates. The cumulative NEE fluxes for Years 1 and 2 follow a similar pattern, but Year 2 is noticeably weaker as a carbon sink and stronger as a carbon source until May. Once the *Miscanthus* began its re-growth in 2008 the cumulative NEE rates for Year 2 increased more rapidly towards a strong carbon source than in Year 1. The final NEE cumulative fluxes for the two years were $-12,676 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ yr}^{-1}$ ($-273 \text{ g C m}^{-2} \text{ yr}^{-1}$) and $-18,171 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ yr}^{-1}$ ($-392 \text{ g C m}^{-2} \text{ yr}^{-1}$) respectively. The difference between the two years, $118 \text{ g C m}^{-2} \text{ yr}^{-1}$, is the equivalent of approximately ten days of CO_2 uptake during the Maximum Growth season.

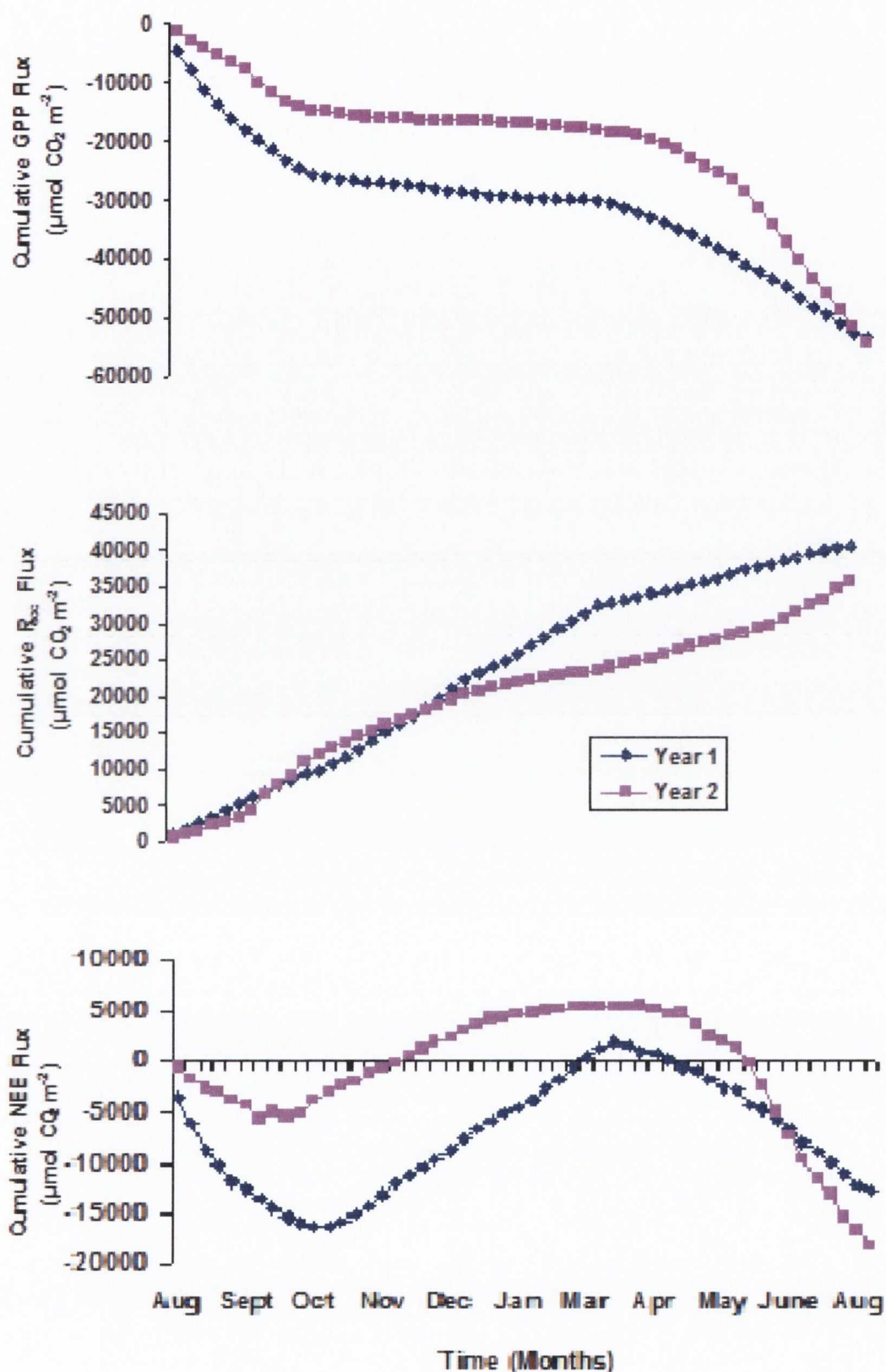


Figure 3.14: Cumulative GPP, Reco and NEE from Year 1 and Year 2. Year 1 relates to measurements made from August 11th 2006 to August 10th 2007. Year 2 relates to measurements made from August 11th 2007 to August 10th 2008. Measurements made over a homogenous *Miscanthus x giganteus* canopy at Oak Park Research Centre, Co. Carlow. Positive values indicate net loss of CO₂ from the system while negative values indicate net uptake of CO₂ by the system.

3.4.2.4: Fluxes and Meteorological Data:

The most significant climatic variables that affect crop development, and by extension NEE fluxes, are radiation, temperature and rainfall. Rainfall events are irregular and if absent for sustained periods drought or water stress conditions can develop. Soil moisture conditions provide a degree of insight into the water stress levels within a crop. They are commonly quantified by soil moisture deficits (SMD), that is the amount of water, expressed as mm of precipitation, required to replenish soil water content to field capacity (Keane, 2001). The Schulte *et al.* (2005) model was used to estimate SMD within the *Miscanthus* stand. Daily and average weekly SMD were calculated for the two calendar years under investigation. Four distinct periods of high SMD developed over the study: in 2007, from March to June and from August to the start of November, and in 2008 effectively from March to August but a rainfall event in July divided this period into two separate phases. High SMD cannot be definitely correlated to water stress in the *Miscanthus* stand, as the crop may possess suitable water stress strategies at the observed SDM levels. However, SMD do provide a good indication that the crop was water-limited. Weekly NEE fluxes (g C m^{-2}) and their corresponding average weekly SMD are displayed in Figure 3.15. High SMD were associated with summer months. The *Miscanthus* stand was at near field capacity throughout the two winter seasons.

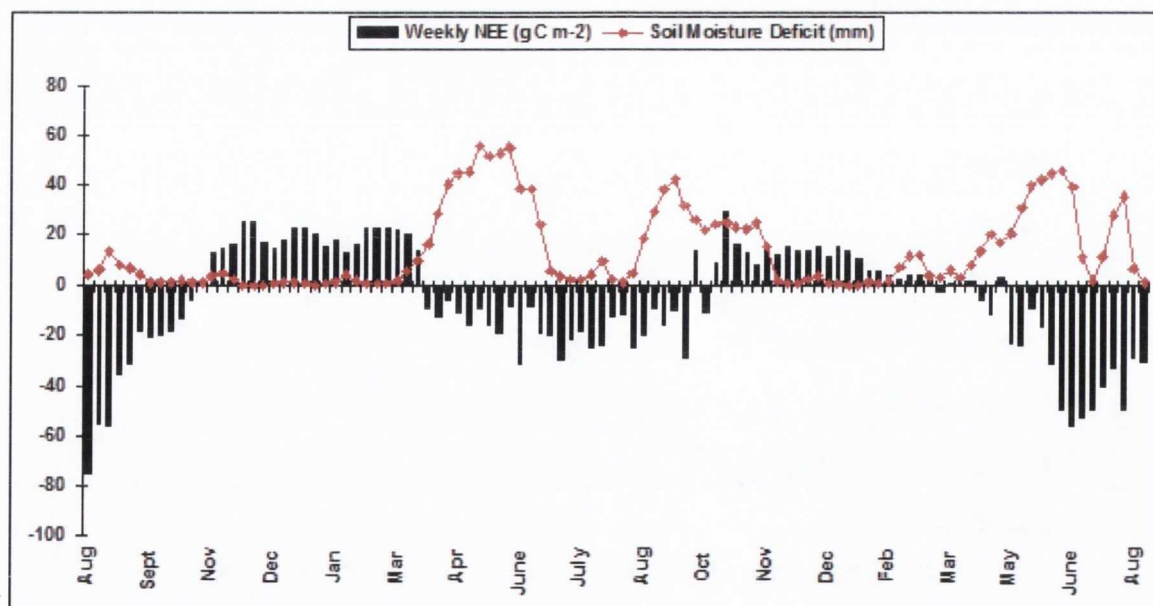


Figure 3.15: Weekly NEE fluxes and corresponding weekly average soil moisture deficit (mm) as determined using the Schulte *et al.* (2005) model. Positive NEE values indicate net loss of CO₂ from the system while negative values indicate net uptake of CO₂ by the system. Measurements made a homogenous *Miscanthus* x *giganteus* canopy at Oak Park Research Centre, Co. Carlow from 11th 2006 to August 10th 2008.

Average weekly PAR and air temperatures were compared to weekly NEE fluxes (Figures 3.16 and 3.17). Defined annual cycles in both meteorological variables were observed. In general, average weekly temperatures above 11 °C were associated with the *Miscanthus* acting as a carbon sink, the crop acted as a net source of carbon below this temperature threshold. Net carbon uptake was associated with average weekly PAR vales over 1000 $\mu\text{mol m}^{-2} \text{s}^{-1}$.

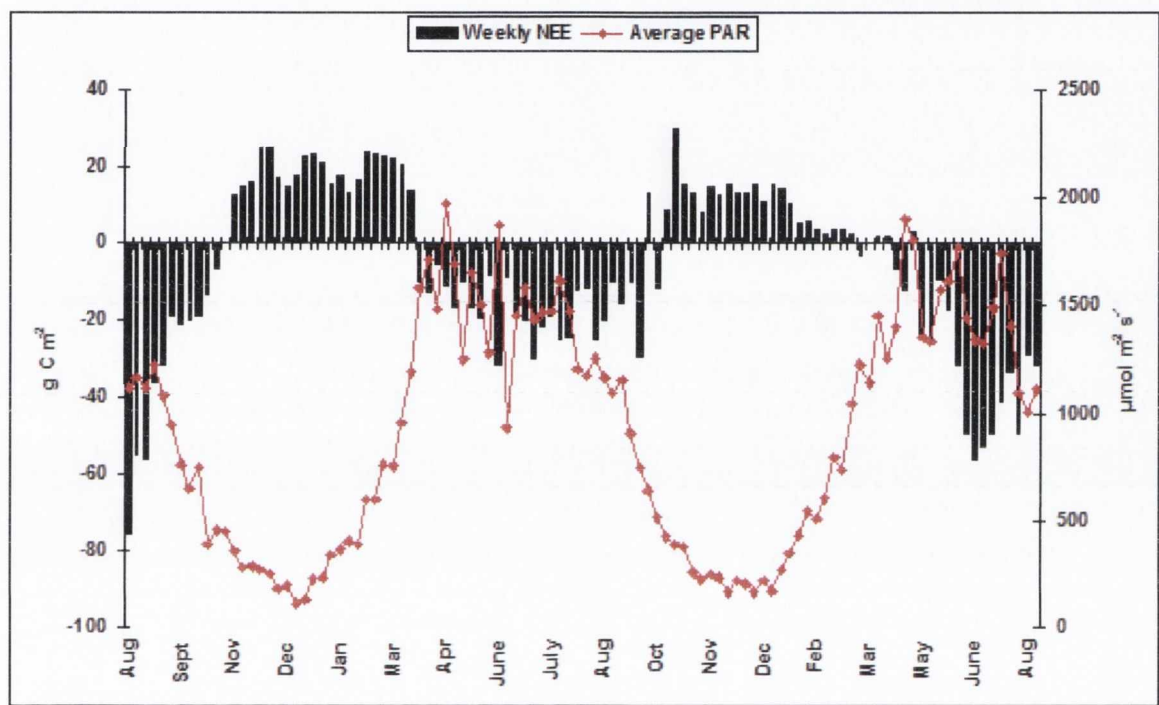


Figure 3.16: Weekly NEE fluxes and corresponding weekly average PAR ($\mu\text{mol m}^{-2} \text{s}^{-1}$). Positive NEE values indicate net loss of CO_2 from the system while negative values indicate net uptake of CO_2 by the system. Measurements made a homogenous *Miscanthus x giganteus* canopy at Oak Park Research Centre, Co. Carlow from 11th 2006 to August 10th 2008.

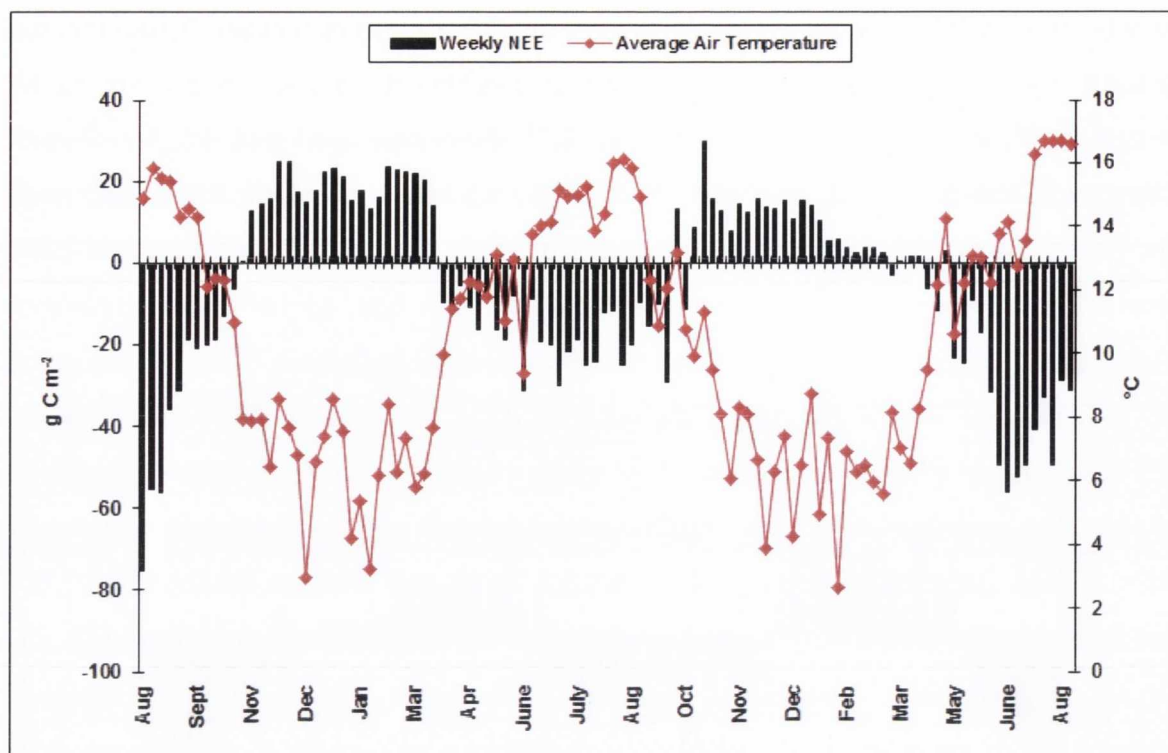


Figure 3.17: Weekly NEE fluxes and corresponding weekly average air temperature (°C). Positive NEE values indicate net loss of CO₂ from the system while negative values indicate net uptake of CO₂ by the system. Measurements made a homogenous *Miscanthus x giganteus* canopy at Oak Park Research Centre, Co. Carlow from 11th 2006 to August 10th 2008.

3.5: Discussion:

This chapter describes CO₂ flux values measured from a *Miscanthus* stand over two calendar years. Traditionally chamber methods are employed for measuring carbon fluxes in ecosystems; these techniques cover limited spatial sampling areas and have the possibility of creating unrealistic micro-climatic conditions (Baldocchi, 2003). EC provides one of the most direct and defensible methods for measuring the NEE of CO₂ over a large sampling area without disturbing the underlying vegetation. Quantifying the fluxes of CO₂ over the crop provides a measure of the potential mitigation of CO₂ emissions into biomass. Under the Kyoto Protocol and EU2020 carbon emissions can be offset by the demonstrable and purposeful removal of CO₂ from the atmosphere. Strategies that increase CO₂ storage in vegetation and soils may constitute the bulk of GHG emission reductions over the next number of years (Wigley *et al.*, 1996).

3.5.1: Eddy Covariance Flux Data Processing and Quality Controls:

Closure of the energy balance during EC flux measurements provides a method through which turbulent (sensible and latent heat fluxes) and available (net radiation and soil heat fluxes) energy can be accounted for (Wilson *et al.*, 2002; Aubinet *et al.*, 2000). The

statistical regression of turbulent energy in relation to available energy in the *Miscanthus* stand showed a 77% closure. This fell within the range of energy balance closure values reported by Aubinet *et al.* (2002) at EUROFLUX sites. Approximately 23% of the available energy within the ecosystem is unaccounted for by the EC measurements, suggesting a systematic underestimation of the energy sinks. Complete energy balance closures are rarely recorded. An average of 80% closure is achieved at FLUXNET sites (Wilson *et al.*, 2002). At the *Miscanthus* site it is likely that energy stores within the canopy and the soil prevent complete closure. The available energy absorbed by the long and numerous *Miscanthus* leaves may represent an undetermined sink. In addition, the positioning of the heat flux plates may, at times of the year, be in constant shade due to the closed crop canopy, thus the ground heat flux would be underestimated. It is possible that the EC tower itself was a contributory factor, dissipating some of the available heat energy. Furthermore, Eitzinger and Kossler (2002) reported that long-wave radiation cools *Miscanthus* stands causing temperature inversion within the canopy at calm nights. This can lead to a significant energy balance closure gap.

The combination of difficulties maintaining power, equipment failure and data rejection meant that 19% of the data stream was missing. These gaps were reconstructed in order to obtain a seasonal and annual carbon balance. Data losses of 25% to 35% have been reported (Law *et al.*, 2002; Baldocchi *et al.*, 2001; Falge *et al.*, 2001). Most data gaps at the *Miscanthus* site were due to power losses. The other main factor contributing to data loss were lack of turbulence at night. The ratio of effective and reliable EC CO₂ fluxes data to night-time data from long-term continuous observations were relatively low, commonly less than 50% (Zhu *et al.*, 2006). Reliable eddy covariance measurements require adequate mixing of the air within the ecosystem and the air above the ecosystem (Lavigne *et al.*, 1997). Turbulence levels are usually described by u^* . There is no universally accepted method of determining the u^* threshold. Researchers often find the threshold by visually examining a scatter plot of night-time fluxes and u^* values, as was the case in this study. This technique is open to criticism due to its subjective nature (Gu *et al.*, 2005) and the assumption that storage and advection are negligible during windy periods (Wofsy *et al.*, 1993; Massman and Lee, 2002). This may not be a valid assumption on sites with heterogeneous canopy covers or topographies, or on sites with a strong spatial distribution of sinks and sources (Marcolla *et al.*, 2003). As the *Miscanthus* stand was homogeneous with no evidence of spatial distribution in sinks or sources the u^* approach was employed. This choice was partly validated by the findings of Aubinet *et al.* (2000) suggesting, that

despite the inter-site variation, a u^* threshold of approximately 0.4 m s^{-1} is typical; average u^* at the *Miscanthus* site was 0.35 m s^{-1} .

The daytime data were gap filled with the Michaelis-Menten function; 70% of the variation in NEE was accounted for by changes in PAR. The Lloyd and Taylor respiration function was used to gap fill night-time data. The function is simplistic and does not account for soil moisture, but it is commonly used and generates reasonable respiration values. In support for not including soil moisture in the model, Qi and Xu (2001) found that when soil moisture was excluded as a variable the temperature effect alone explained 82% of the temporal variation in CO_2 fluxes from soil in a forest ecosystem. 83% of the variation in NEE was accounted for by changes in air temperature at the *Miscanthus* site while only 53% of the variation was accounted for by soil temperature. It is not clear why air temperature was better correlated to night-time fluxes than soil temperature. It is possible that air temperature has a more direct influence on the exposed leaf litter and above ground biomass in the stand. In addition, the large quantities of leaf litter may insulate the soil and dampen the diurnal and seasonal variation. The effect of the different gap filling methods on the annual sums of NEE are modest, with most falling within a range of $\pm 25 \text{ g C m}^{-2} \text{ yr}^{-1}$ (Moffat *et al.*, 2007) and so the practice of filling missing data itself did not produce a significant source of bias error.

3.5.2: Eddy Covariance and Meteorological Data:

A close relationship between PAR and net carbon uptake existed; greater carbon assimilation was linked to increasing PAR levels. The importance of PAR levels was lessened during the fallow period (November to March) when the *Miscanthus* crop senesces. Even though the *Miscanthus* is incapable of photosynthesizing during this period the ecosystem still displayed low levels of GPP fluxes. These were attributed to the understory vegetation taking advantage of greater light penetration following winter senescence. Vegetation surveys from chapter 2 showed that *Agrostis stolonifera*, *Poa annua* L. and *Rubus fruticosus* L. were common at the *Miscanthus* stand during this time. A trend of increasing carbon uptake with increasing temperature was seen. Average weekly temperatures above 11°C were associated with the *Miscanthus* acting as a carbon sink, the crop acted as a net source of carbon below this temperature threshold. High temperatures usually occur with high PAR levels when GPP fluxes are the prevailing NEE component.

To consider the effect of water stress on NEE fluxes a soil moisture deficit (SMD) model (Schulte *et al.*, 2005) was employed to estimate soil moisture conditions. The model, which was critically reviewed by Kerebel *et al.* (2010), was based on the following site-specific data: soil class, latitude, longitude, rainfall, wind speed, radiation and temperature. SDM does not necessarily indicate drought conditions except when the deficits are much greater than the average for the time of year. The SDMs recorded in the summer months at Oak Park were not substantially different to values recorded in previous years at the Oak Park meteorological station (data extrapolated from Met Eireann Bulletin Reports), suggesting drought conditions were not experienced during the experimental period. The ability of *Miscanthus* to adapt to water stresses is under debate. Foti *et al.* (2003) have observed a decrease in leaf transpiration and stomatal conductance at low soil water conditions, which did not immediately affect leaf net photosynthesis or plant growth; while, Clifton-Brown *et al.* (2002) reported that *Miscanthus* does not have a flexible water saving strategy.

The *Miscanthus* stand acted as a net carbon sink absorbing $2.7 \text{ t C ha}^{-1} \text{ yr}^{-1}$ and $3.9 \text{ t C ha}^{-1} \text{ yr}^{-1}$ over the two years under examination with corresponding harvest yields of 10.15 and $10.17 \text{ t DM ha}^{-1}$. The *Miscanthus* stand was a carbon sink during the Early and Maximum Growth periods (April to October) and a net carbon source during the Litter Fall and Senescence stages (November to March). Year 1 had greater net carbon uptake compared to Year 2 for most months in the study period, it was only in June 2008 that Year 2 NEE fluxes surpassed those measured in Year 1 (Figure 3.14). Studies have indicated that shifts in respiration can be the dominant control on interannual variation in the net carbon sink-source status of an ecosystem (Valenti *et al.*, 2000; Saleska *et al.*, 2003; Griffis *et al.*, 2004). Year 2 had lower R_{eco} fluxes in eight months compared to Year 1 (Figure 3.14). Litter fall at the *Miscanthus* site was an important factor in ecosystem respiration; litter can contribute a significant amount of CO_2 to an ecosystem (Luo and Zhou, 2006; Wong *et al.*, 1999). There was markedly less litter fall in Year 2 ($3.08 \text{ t DM ha}^{-1}$) compared to Year 1 ($4.65 \text{ t DM ha}^{-1}$) with corresponding litter fall rates of 3.18 and $9.12 \text{ g DM m}^{-2} \text{ day}^{-1}$. Higher rates of R_{eco} fluxes were recorded during and immediately post litter fall in Year 1 compared to Year 2, relating to the greater quantity of substrate available for decomposition.

The difference between the NEE of the stand over the two years was $118 \text{ g C m}^{-2} \text{ yr}^{-1}$; this is the equivalent of approximately ten days of CO_2 uptake during the Maximum Growth

season. Therefore, favourable meteorological conditions during the growing season can greatly improve the carbon sink strength of *Miscanthus*. The corollary of which is, if the summer months had poor weather conditions the carbon sink strength of the crop would be significantly reduced; thus impacting the potential of *Miscanthus* in offsetting CO₂ emissions.

Currently, there is only one other study investigating CO₂ fluxes above a *Miscanthus x giganteus* crop. This study is being conducted by the University of Southampton in the United Kingdom, in partnership with the Carbo-BioCrop Project. The study began in 2009 with the goal of improving the current understanding of how bioenergy crops influence the UK greenhouse gas balance. At the site in Southampton the *Miscanthus* stand had a net carbon uptake of 1.28 t C ha⁻¹ yr⁻¹ in 2009 with an NEE of CO₂ for *Miscanthus* -770g C m⁻² h⁻¹ in the growing season (Drewer *et al.*, 2011). This was a lower NEE than those registered at the Oak Park site. The differences maybe attributed to differences in crop age, meteorological conditions, management practices and the field site (including soil fertility, drainage and field orientation). Despite the difference in actual NEE values the crop is consistently performing as a net carbon sink. It would be interesting to compare EC fluxes from the two sites and investigate where similarities and divergences in the data occur. Information gathered from a comparative study could promote optimal crop management in order to maximise the carbon sink strength of the crop over its life cycle.

Shimoda *et al.* (2009; 2005) measured CO₂ exchange above a high-yield grassland dominated by *Miscanthus sinensis* in Japan reporting that the grassland behaved as a weak carbon sink or was near carbon neutral (-78 and 17 g C m⁻² yr⁻¹). *M. sinensis* has a similar physiology to *M. giganteus*; however, *M. giganteus* grows considerably taller and has broader leaves. Near the Carlow site a small amount of *M. sinensis* was grown; no quantitative measurements were carried out on these plants but based on visual inspection the *M. giganteus* plants were approximately 50% taller with longer, wider leaves. Considering the larger above ground biomass it is not unusual that the *M. giganteus* stand acted as a stronger carbon sink compared to the *M. sinensis* grassland. Li *et al.* (2003) reported similar values to Shimoda *et al.* (2009) with a peak NEE value of -57.4 μmol CO₂ m⁻² s⁻¹ over a C3/C4 co-occurring wet temperate *Miscanthus*-type grassland in the Kanto Plain of Japan in the 1999 growing season.

There are a limited number of further studies that can be meaningfully compared to the *Miscanthus* data. In the next few years the Carbo-BioCrop Project will be releasing NEE values over a range of bioenergy crops in the UK. At that point more detailed comparisons of crop net ecosystem exchanges can be performed. In Ireland there are also a limited number of published eddy covariance experiments. Peichl *et al.* (2011) reported on six years of eddy covariance over an intensively managed grassland in Southern Ireland. They found that the site acted as a considerable carbon sink with an annual NEE range of 2.45 to 2.84 t C ha⁻¹ yr⁻¹. This range is close to that of the *Miscanthus* stand in Year 1 (2.73 t C ha⁻¹ yr⁻¹). Intensively managed grasslands tend to have enhanced uptake of atmosphere CO₂ (Gilmanov *et al.*, 2010; Allard *et al.*, 2007) compared to temperate grasslands, which are often carbon neutral or weak carbon sinks (Jones and Donnelly, 2004). Jacobs *et al.* (2007) reported mean annual NEE amounts to -0.65 ± 0.85 t C ha⁻¹ yr⁻¹ for four natural grasslands, two production grasslands and two meteorological stations in the Netherlands.

There is an abundance of eddy covariance studies over a range of different forest types and, to a smaller degree, over different agricultural sites (see CarboEurope; AmeriFlux; AsiaFlux, OzFlux, AfriFlux, FLUXNET-Canada, ChinaFlux, USCCC and TCOS-Siberia). The advantage of comparisons to the *Miscanthus* stand are questionable due to considerable physiological and geographical differences. Nevertheless, to place the *Miscanthus* data in context the following ranges have been reported in the literature: on average crops and grasslands act as carbon sources with an annual NEE of +0.40 t C ha⁻¹ yr⁻¹ (at 11 sites in the AmeriFlux Project); while forests act as carbon sinks with NEE values averaging between -1.00 to -3.00 t C ha⁻¹ yr⁻¹ (Hollinger *et al.*, 2010). Higher forest sink strengths have been recorded elsewhere, up to -6.29 t C ha⁻¹ yr⁻¹ in Oak Ridge, Tennessee (Wilson and Baldocchi, 2001).

3.6: Summary:

- Over the duration of this experiment the *Miscanthus* stand acted as a net sink of carbon, assimilating 6.66 t C ha^{-1} over the twenty-four months.
- There was incomplete energy balance closure at the site (77%), but the level of closure was considered adequate and within published parameters.
- Gap filling of day and night-time EC data were required and were successfully carried out using the Michaelis-Menten and Lloyd-Taylor models with a high level of robustness.
- The *Miscanthus* stand was a carbon sink during the Early and Maximum Growth periods (April to October) and a net carbon source during the Litter Fall and Senescence stages (November to March).
- Lower R_{eco} fluxes in Year 2 appeared to be the dominant control on interannual variation in the net carbon sink-source status of crop.

A possible future study would involve comparing the eddy covariance fluxes measured over the *Miscanthus* stand in Oak Park with those currently being recorded in the Carbo-BioCrop study.

Chapter 4

Chamber Measurements: Soil and Plant CO₂ Fluxes

4.1: Introduction:

The movement of carbon through *Miscanthus* biomass (Chapter 2) and between the atmosphere and the crop (Chapter 3) has already been presented. This chapter describes the direct fluxes of CO₂ from the soil and plants within the *Miscanthus* stand using the chamber method. These measurements are important for comparing the component fluxes (GPP and R_{eco}) of the eddy covariance data with scaled-up field measurements and are also essential in investigating the relationship between carbon fluxes and environmental conditions, such as soil temperature and PAR levels.

Soils are an important component in the carbon cycle, as, after oceans, they are the largest pool in the global carbon cycle (Rayment and Jarvis, 2000). The predominant processes involved in carbon sequestration into the soil include litter fall, root turnover and biomass decomposition (Hogberg *et al.*, 2001). CO₂ release from the soil is mainly through the respiration of roots and soil organisms and mineralisation of organic matter (Hanson *et al.*, 2000). The carbon released from the soil accounts for 20-40% of the annual atmospheric CO₂ input, emitting approximately 68 to 100 Pg C yr⁻¹ globally (Raich and Schlesinger, 1992).

Plant-derived CO₂ has a quick turnover rate; the carbon released by roots and rhizomicrobial activity remains in the soil for a period of minutes to days (Kuzytacou *et al.*, 1999; Kuzytacou, 2006). In contrast, the carbon released in the degradation of soil organic matter by soil microbes can take from weeks to centuries (Hahn and Bauchmann, 2004). Nearly all of the soil CO₂ production is released into the atmosphere; only a small fraction (c. 0.3%) is dissolved into the soil solution and escapes into the ground water (Edwards and Harris, 1977). The primary mechanism for transport of CO₂ from the soil to the atmosphere is via diffusion through a network of air or water-filled pore spaces (Simunek and Suarez, 1993). Most of the soil CO₂ production occurs in the surface litter and uppermost regions of soil, due to rapid decomposition rates in the litter layer and the large proportion of root biomass in the top layers of soils (Singh and Gupta, 1977; Bowden *et al.*, 1993; Law *et al.*, 1999).

Soil respiration depends on weather conditions in the short term, with changes in temperature and rainfall having the strongest influence (Tackle *et al.*, 2003). Variations on an inter-annual scale are attributed to variability in climatic conditions, as they affect plant phenology and growing seasons (Epron *et al.*, 2004; Curiel-Yuste *et al.*, 2004). Temperature is a primary factor in soil carbon cycling (Singh and Gupta, 1977; Weber, 1985; Raich and Schlesinger, 1992); Lloyd and Taylor (1994) stated that the temperature sensitivity of soil respiration is best described by an empirical relationship. Q_{10} represents the difference in respiration rates over a 10 °C interval. In the literature there is a strong debate as to the best calculation of Q_{10} ; which equation best describes the dependence of respiration on temperature and what temperature range should be used. A number of authors have used different equations to describe the temperature response (Johnson and Thornley, 1985; O'Connell, 1990; Kirschbaum, 1995; Fang and Moncrieff, 2001). Soil moisture is also an important factor in regulating soil respiration; in general, soil CO₂ fluxes are lowest under dry conditions, highest at near field capacity and decrease in waterlogged soils when anaerobic conditions depress microbial activities (Xu and Qi, 2001; Linn and Doran, 1984). The soil moisture is largely determined by rainfall events. Fierer and Schimel (2002) described the effect of rainfall on respiration as follows: initially, soils release a pulse of CO₂ during rainfall due to degassing, a subsequent increase in soil respiration follows after several hours or days due to increased microbial activity, and finally, after a number of days an increase in root respiration is usually recorded due to increased root growth and improved above ground photosynthesis. The production and turnover of below ground biomass adds carbon to the soil (Zan *et al.*, 2001). The allocation of carbon to below ground structures is one of the most important but least well-quantified fluxes of carbon in terrestrial ecosystems (Davidson *et al.*, 2002). The prolific and deep rooting system of perennials strongly affects carbon sequestration by significantly increasing the amount of organic matter in the soil (Lemus and Lal, 2005).

Photosynthesis has an impact on soil respiration (Heilmeyer *et al.*, 1997). Janssens *et al.* (2001) reported that the primary influence on both auto and heterotrophic respiration is annual gross primary production; while, Raich and Schlesinger (1992) demonstrated a strong linear correlation between annual soil respiration and net primary production. A study in a Scots Pine Forest showed that reducing photosynthesis was correlated to a 50% reduction in soil respiration (Hogberg *et al.*, 2001). Furthermore, photosynthesis influences the production of plant detritus, which is closely related to soil respiration, with respiration rates increasing due to the amount of litter production (Maier and Kress, 2000).

Conversely, Ingram and Fernandes (2001) suggested that large amounts of litter have a cooling effect on soil lowering biological activity and potentially reduce soil respiration.

There are a number of different methods for measuring total soil respiration including micrometeorological techniques, and open-, closed-, or flow-through chambers. Portable IRGAs and chamber systems are the most popular method as they can be used in field conditions and readily cover a wide spatial distribution. Chamber techniques have been reviewed in the literature (Hutchinson and Livingston, 2002; Holland *et al.*, 1999, Rochette and Hutchinson, 2005). The principle of soil chamber measurements is that CO₂ emissions from the soil accumulate inside the chamber space and the rate of CO₂ efflux is estimated by the change in CO₂ concentration over time (dC/dT). However, when a chamber is placed on moist soil, water vapour increases and displaces the chamber air causing a dilution of CO₂ concentrations; therefore, dC/dT appears lower than it truly is. For this reason, chamber measurements cannot be made during or immediately after a rainfall event. This is a major drawback of the technique (Xu *et al.*, 2009). In addition, surface chamber measurements do not necessarily reflect the varying rates of respiration with depth. However, several researchers have argued that surface measurements of soil respiration are sufficient due to the higher CO₂ production rates in the upper portions of the soil profile (Jassal *et al.*, 2005; Davidson *et al.*, 2006). Albanito (2009) reported that in a *Miscanthus* stand over 12 months the top layer of soil (0-10 cm) contributed an average of 59% of the total soil efflux.

Several reviews have been published on the topic of partitioning sources of CO₂ efflux from the soil (Baggs, 2006; Kuzyakou, 2006; Hanson *et al.*, 2000). All studies agreed that the separation of autotrophic and heterotrophic respiration is a major challenge at this point in time due to the limitations in current techniques. Numerous methods have been devised to partition fluxes namely: root exclusion treatments (Epron *et al.*, 1999), isotopic labelling experiments (Andrews *et al.*, 1999) and physically separating components and measuring respiration from each component in isolation (Thierron and Laudelout, 1996). It was not considered feasible to attempt any of these methods in this project.

CO₂ fluxes between the plant and the atmosphere are another important component of the carbon cycle. The main input of carbon into terrestrial ecosystems is via photosynthesis. The conversion of atmospheric CO₂ into carbohydrates through photosynthesis is termed gross primary production (GPP). These carbohydrates can be used to form new plant tissues during growth or metabolised and returned to the atmosphere through autotrophic

respiration (R_a). The balance between carbon fixation in photosynthesis and carbon loss in plant respiration is net primary productivity (NPP); strongly influenced by light levels, CO_2 concentrations and temperature. Placing a *Miscanthus* plant in an enclosure, attached to a gas analyser, would be the ideal technique for monitoring the exchange of CO_2 between the plant and the atmosphere but the size of the *Miscanthus* crop at peak growth and the rapid change in height over the growing season means that the approach is impractical. Instead, smaller chambers were used to assess carbon fluxes from the leaves. Leaf chambers generally consist of a Perspex window surrounded by a neoprene gasket, which is clamped onto a leaf, of known area, and a gas analyser records gas exchange. Leaf chambers are widely used and have been reviewed by Long *et al.* (1996) and Long and Hällgren (1993).

4.1.1: Aims:

The primary aim of carrying out chamber measurements was to assess the CO_2 fluxes from the soil and leaves within the *Miscanthus* stand in Oak Park. The relationship between soil respiration and soil temperature and moisture was investigated. Soil analyses were conducted in order to characterise the soil under the *Miscanthus* crop. Leaf photosynthesis measurements were carried out to examine whether *Miscanthus* was light saturated in field conditions. In addition, the impact of a closed canopy on photosynthetic levels was studied by measuring photosynthesis from sunlit and shaded leaves.

4.2: Methodology:

4.2.1: Soil Sampling and Analysis:

A soil sampling campaign was carried out at the *Miscanthus* stand in November 2008. Two trenches were dug to the bedrock (approximately 0.25 m x 0.5 m x 0.8 m) to carry out soil profile analysis. The soil type was determined following the classification scheme for England and Wales (Avery, 1980). In addition, ten plots were randomly chosen within the eddy covariance (EC) flux footprint; but soil sampling was delayed until after the conclusion of the EC experiment in order not to disturb soil respiration fluxes. Small trenches of approximately 0.4 m x 0.3 m were dug to a depth of 0.5 m. Soil cores (8 cm diameter and length) were removed from three sides of each trench at 10-15 cm and 30-35 cm. The soil cores were dried to a constant weight at 65 °C. All visible organic material

was removed and the soil samples were then sieved through a 2 mm mesh and were analysed as follows:

Soil pH was determined in water extracts according to Hendershot and Lalande (1993) using an Orion 3 Star pH meter (Thermo Fisher Scientific Inc., Michigan, USA). pH tests were carried out on 6 soil samples per trench; three samples at both the 10-15 cm and 30-35 cm depths. The SOM content of the *Miscanthus* soil samples was determined using the LOI methodology described by Nelson and Sommers (1996). The LOI test was carried out on soil samples taken from 10-15 cm depths. Three samples per trench were used. The loss-on-ignition is calculated as follows:

$$\text{LOI \%} = \frac{(\text{Sample weight after drying at } 105^{\circ}\text{C}) - (\text{Sample weight after burning at } 550^{\circ}\text{C})}{\text{Sample weight after drying at } 105^{\circ}\text{C}} * 100$$

Particle size distribution was measured using the hydrometer methodology reported by Allen (1981). Particle size distribution was determined on two soil samples from each trench at the 10-15 cm and 30-35 cm depths. The particle size distribution was calculated using the following equations:

$$\begin{aligned}\text{Sand \%} &= ((25 - \text{AT}_{\text{sct}} * 0.5) / 25) * 100 \\ \text{Clay \%} &= ((25 - \text{AT}_{\text{ct}} * 0.5) / 25) * 100 \\ \text{Silt \%} &= 100 - (\text{Sand \%} + \text{Clay \%})\end{aligned}$$

Where AT_{sct} and AT_{ct} are the temperature corrected amounts of 'silt and clay' and 'clay' (g) in suspension respectively, and were calculated as follows:

$$\begin{aligned}\text{AT}_{\text{sct}} &= \text{A}_{\text{sc}} + \text{T}_{\text{sc}} \\ \text{AT}_{\text{ct}} &= \text{A}_{\text{c}} + \text{T}_{\text{c}}\end{aligned}$$

Where AT_{sc} and AT_{c} are the amount of 'silt and clay' and the amount of 'clay' (g L^{-1}), obtained using the specific gravity measurements from the hydrometer reading. T_{sc} and T_{c} are temperature correction factors, which were calculated as:

$$\begin{aligned}\text{T}_{\text{sc}} &= 0.36 * (\text{2min temperature reading} - 20^{\circ}\text{C}) \\ \text{T}_{\text{c}} &= 0.36 * (\text{24 hour temperature reading} - 20^{\circ}\text{C})\end{aligned}$$

The soil texture was determined using a standard US Department of Agriculture (USDA) classifications of size definitions textural triangle.

For bulk density determinations a total of 50 soil samples were taken from the *Miscanthus* stand; 5 samples were taken from 10 plots at depths of 0-5 cm, 10-15 cm, 20-25 cm, 30-35 cm, 40-45 cm, representing the surface-level, the A horizon and the B horizon levels in the soil profile. Cutters were gently hammered into the soil and removed carefully to avoid damage. The ends of the samples were trimmed level with the corer. Any samples that were not fully filled with soil were rejected. The fresh weight of the 'cutter and soil' was measured to three decimal places within 60 minutes of extraction. The cores were dried at 105°C to a constant weight. The 'cutter and soil' and then the 'cutter' alone were weighed.

The internal volume of the cutter was measured. The following calculations were made:

$$\text{Bulk Density (g/cm}^3\text{)} = \frac{\text{Mass of dry soil (g)}}{\text{Volume of core (cm}^3\text{)}}$$

$$\text{Gravimetric Water Content (\%)} = \frac{\text{Mass of wet soil (g)} - \text{Mass of dry soil (g)}}{\text{Mass of dry soil (g)}} * 100$$

4.2.2: Soil Chamber Measurements:

Measurements of soil respiration were made using a CIRAS-1 portable CO₂ analyser and a SRC-1 soil respiration chamber (PP Systems Inc., Massachusetts, USA). Measurements were made weekly or biweekly, weather depending, between 9.30 and 11 am following the findings that measurements made between these hours share a closer resemblance to the diurnal mean flux than measurements made in the afternoon (Davidson *et al.*, 1998). Soil respiration varies spatially and so a wide range of locations, were used to assess the spatial variation across the experimental site. 17 sampling sites were chosen, 10 m apart, along a transect that ran diagonally through the EC flux footprint. Before each measurement the area was cleared of leaf litter, plant debris and living material. The chamber was pushed firmly into the soil to form a strong seal. No collars were used as it was felt it would alter the soil environments, particularly by pooling precipitation. Pumpanen *et al.* (2004) showed that the use of collars within an unmodified SRC-1 chamber caused an overestimation of fluxes by as much as 33%. To avoid the influence of pressure differentials caused by sealing the chamber, time was given to ensure pressure equilibration before measurements started (Healey *et al.*, 1996; Hanson *et al.*, 1993). Concurrent to soil respiration measurements, soil temperature and moisture measurements at a depth of 5 cm were also made (WET-2 Sensor, Delta-T Devices Ltd., Cambridge, UK).

4.2.3: Leaf Chamber Measurements:

A leaf chamber measurement campaign was established for the *Miscanthus* stand. Five *Miscanthus* plants were chosen along a transect 10 m apart. The plants were labelled with coloured cable ties for identification, but not in a manner that would restrict growth. The plants were visited regularly from June 28th 2007 to October 16th 2007. A diurnal experiment was carried out on August 11th. At each visit the following measurements were recorded: stem height, number of leaves present, health of each leaf and the height of each internode. An ADC-LCA 4 leaf chamber system (ADC Bioscientific Ltd, Herts, U.K.) was

employed. Gas exchange measurements were made on sunlit and shaded leaves on the 5 plants throughout the day from 9am to 5pm. Sunlit leaves were defined as the most recently fully expanded leaf; shaded leaves were defined as leaves 1 m below the top of the canopy, similar to Dohleman and Long (2009). Dew was often present on the leaves at morning measurements, in these cases the leaves were blotted dry before being enclosed in the leaf chamber. Measurements were recorded once CO₂ uptake stabilized, typically under a minute. All measurements were made under ambient conditions. PAR levels were measured using a point LI-COR quantum sensor and photometer (LI-COR Biosciences, Nebraska, USA), leaf temperature was measured using a RS thermocouple (Radionics Ltd, Dublin, Ireland).

4.3: Results:

4.3.1: Soil Analysis:

The soil was classified as a grey-brown podzolic soil type (Avery, 1980). This coincides with the findings in the General Soil Map of Ireland (1:575,000 scale) that places Oak Park in the Grey Brown Podzolic 75% classification (Gardiner and Radford, 1980). The profile contained an O horizon, approximately 3 cm thick consisting of leaf litter and plant residue in different stages of decomposition, an A horizon approximately 35 cm deep of sandy loam, and a sand and gravel Bh horizon to the bedrock approximately 80 cm deep. A similar soil profile was reported by Albanito *et al.* (2009) in a neighbouring *Miscanthus* stand. The results from the soil analyses are summarised in the Tables 4.1 and 4.2.

Table 4.1: Soil particle distribution of soil samples taken from the *Miscanthus* stand in November 2008.

Analysis	Depth (cm)	n	% Sand	% Clay	% Silt	Soil Classification
<i>Soil Particle Distribution</i>	10-15	10	78.9	16.1	4.9	Sandy Loam
	30-35	10	74.4	16.8	8.7	Sandy Loam

Table 4.2: pH, L.O.I %, bulk density (g cm^{-3}) and gravimetric water content (%) of soil samples taken from the *Miscanthus* stand in November 2008.

Analysis	Depth (cm)	n	Mean	Std error ($\pm$)
<i>pH</i>	10-15	30	7.26	0.08
	30-35	30	7.47	0.02
<i>L.O.I (%)</i>	10-15	30	6.58	1.01
<i>Bulk Density (g cm^{-3})</i>	0-5	10	0.85	0.03
	10-15	10	0.93	0.03
	20-25	10	0.99	0.02
	30-35	10	1.05	0.02
	40-45	10	1.13	0.01
<i>Gravimetric water content (%)</i>	0-5	10	28.13	1.61
	10-15	10	26.66	1.02
	20-25	10	26.86	1.34
	30-35	10	22.63	1.98
	40-45	10	23.24	1.85

4.3.2: Soil Respiration:

The maximum, minimum and average soil respiration rates from the *Miscanthus* stand ($n=17$) for each season are displayed in Table 4.3. The values are comparable with the soil respiration rates under the nearest *Miscanthus* stand (Albanito, 2009). Maximum respiration was recorded in the summer months ($10.55 \text{ g CO}_2 \text{ m}^{-2} \text{ day}^{-1}$), minimum values were seen in the winter months ($0.52 \text{ g CO}_2 \text{ m}^{-2} \text{ day}^{-1}$) and an annual mean respiration rate of $6.59 \text{ g CO}_2 \text{ m}^{-2} \text{ day}^{-1}$ was calculated for the stand. Spatial variation between the 17 sampling sites was quantified using the co-efficients of variation (CV). Over the experimental period the average CV was 34%, this fell to 19% during the growing season (July to September). Figure 4.1 shows the weekly mean soil respiration rates from the *Miscanthus* stand between the October 23rd 2006 and March 2nd 2008. The greatest variations in respiration between sampling dates were seen between May and August 2007 when the *Miscanthus* was undergoing rapid growth. More constant respiration rates were recorded between sampling dates in the two winter seasons of 2006 and 2007.

Table 4.3: The seasonal minimum, maximum and average soil respiration rates from the study site (Oak Park 1) and the neighbouring *Miscanthus* stand (Oak Park 2) (Albanito, 2009). Oak Park 1 measurements were made at the soil surface; Oak Park 2 measurements were made at 0-10 cm depths.

Sampling Period	Site	Soil Respiration Rates (g CO ₂ m ⁻² day ⁻¹)		
		Min.	Max.	Mean
Winter	Oak Park 1	0.52	6.64	3.90
	Oak Park 2	0	7	1.3
Spring	Oak Park 1	1.71	7.63	4.07
	Oak Park 2	0.03	15	5.2
Summer	Oak Park 1	3.36	10.55	5.89
	Oak Park 2	0	27	8.7
Autumn	Oak Park 1	3.61	6.15	4.53
	Oak Park 2	0.03	16.8	8.3

Soil temperature was measured at a depth of 5 cm at each sampling site. Over the experimental period the average soil temperature was 10.9 °C. The maximum temperature, 18.9 °C, was recorded in June 2007; the minimum temperature of 1 °C was observed on the 23rd December 2006. Soil temperature exhibited a well-defined annual cycle (Figure 4.2).

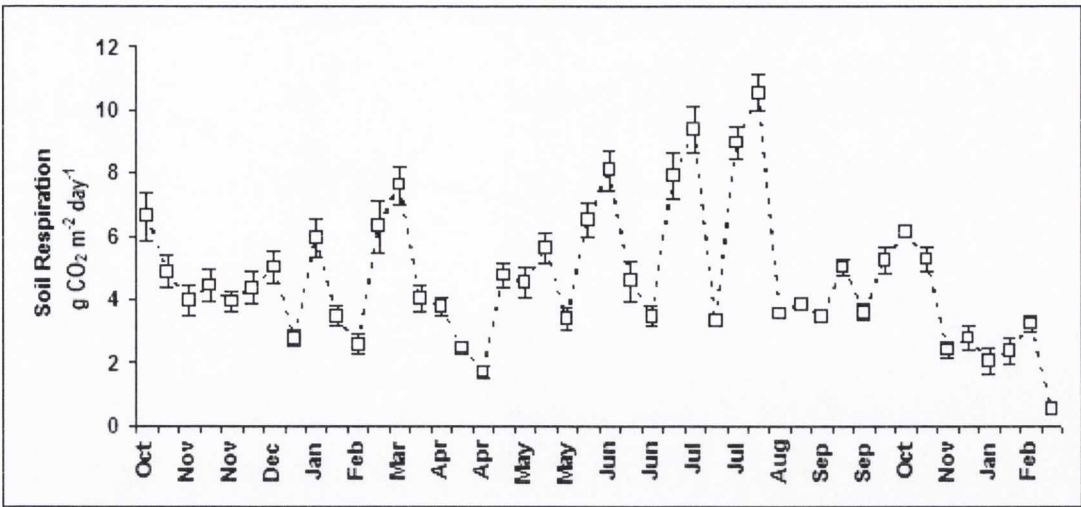


Figure 4.1: Mean soil respiration rates from 17 sampling sites within the *Miscanthus* stand in Oak Park Research Centre, Co. Carlow, between the 23rd of October 2006 and the 2nd of March 2008. Error bars are $\pm$ standard error

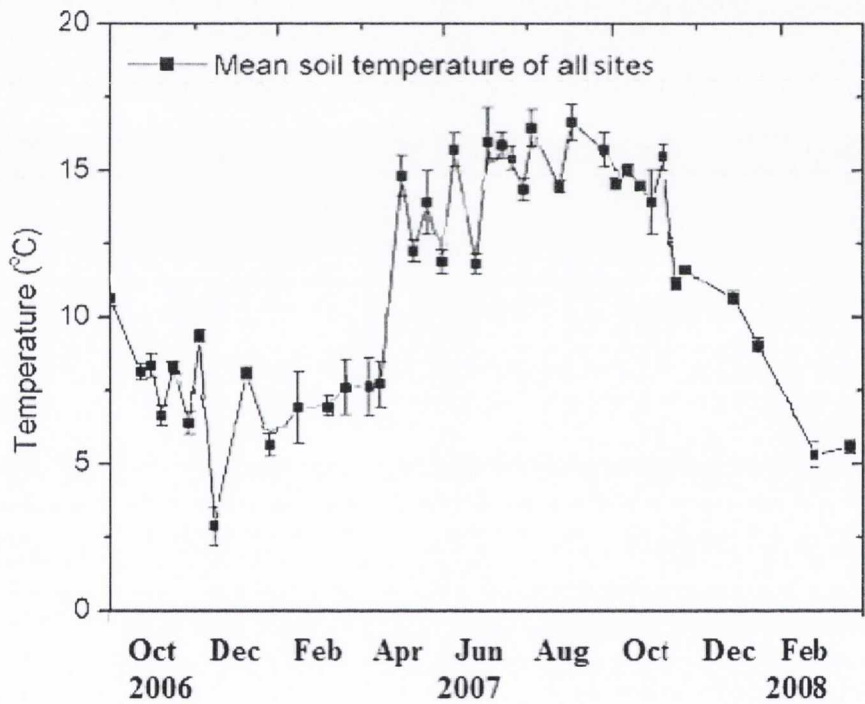


Figure 4.2: Mean soil temperature measurements from 17 sampling sites within the *Miscanthus* stand in Oak Park Research Centre, Co. Carlow, between the 23rd October 2006 and the 2nd March 2008. Error bars are $\pm$ standard error

To test the correlation of soil respiration with soil temperature a Pearson Correlation test, at 95% confidence, was performed on the data. Soil respiration and soil temperature had a correlation r value of 0.45 (P value, 0.002) showing an intermediate strength correlation. Figures 4.3 and 4.4 show the relationship between soil temperature and respiration.

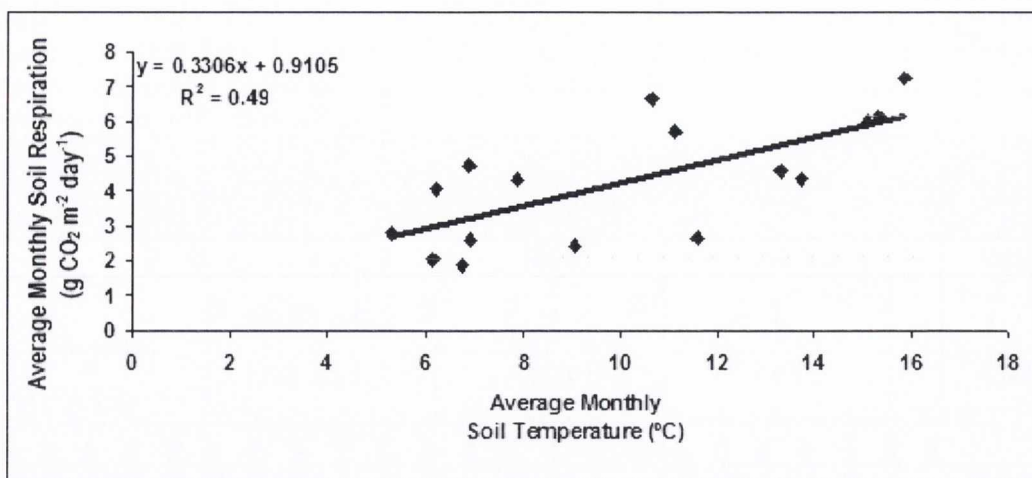


Figure 4.3: The response of average monthly soil respiration (g CO₂ m⁻² day⁻¹) to soil temperature (°C) in the *Miscanthus* stand over 16 months.

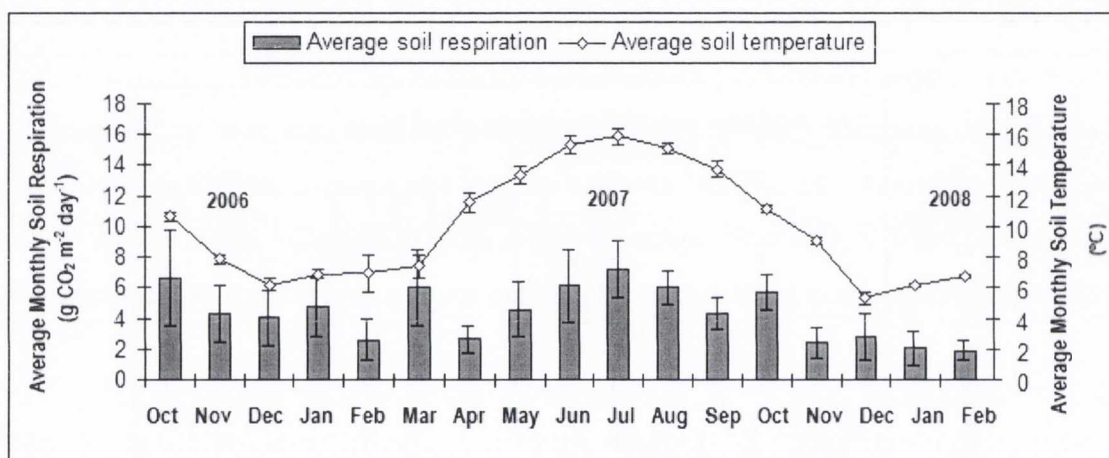


Figure 4.4: Comparing average monthly soil respiration (g CO₂ m⁻² day⁻¹) to monthly soil temperature (°C) in the *Miscanthus* stand over 16 months. Error bars represent $\pm$ standard deviation.

Respiration rates usually increase exponentially with temperature and are regularly described by a Q10 value. Figure 4.5 displays the *Miscanthus* soil respiration data from the Q10 equations of Fang and Moncrieff (2001) and Lloyd and Taylor (1994), detailed below, as well as a simple linear fit. The Q10 exponential models do not greatly describe the respiration-temperature relationship at the *Miscanthus* stand any better than a simple linear model.

Fang and Moncrieff:

$$Q_{10} = (R_2 / R_1)^{10 / (T_2 - T_1)}$$

Where R_1 and R_2 are respiration rates at temperatures T_1 and T_2 respectively.

Lloyd and Taylor:

$$R_{eco} = R_{10} \times e^{\left(E_0 \left(\frac{1}{T_{ref} - T_0} - \frac{1}{T_K - T_0} \right) \right)}$$

Where R_{10} is the reference respiration at 10 °C, E_o is set at 309 K. T_k is air temperature in K.

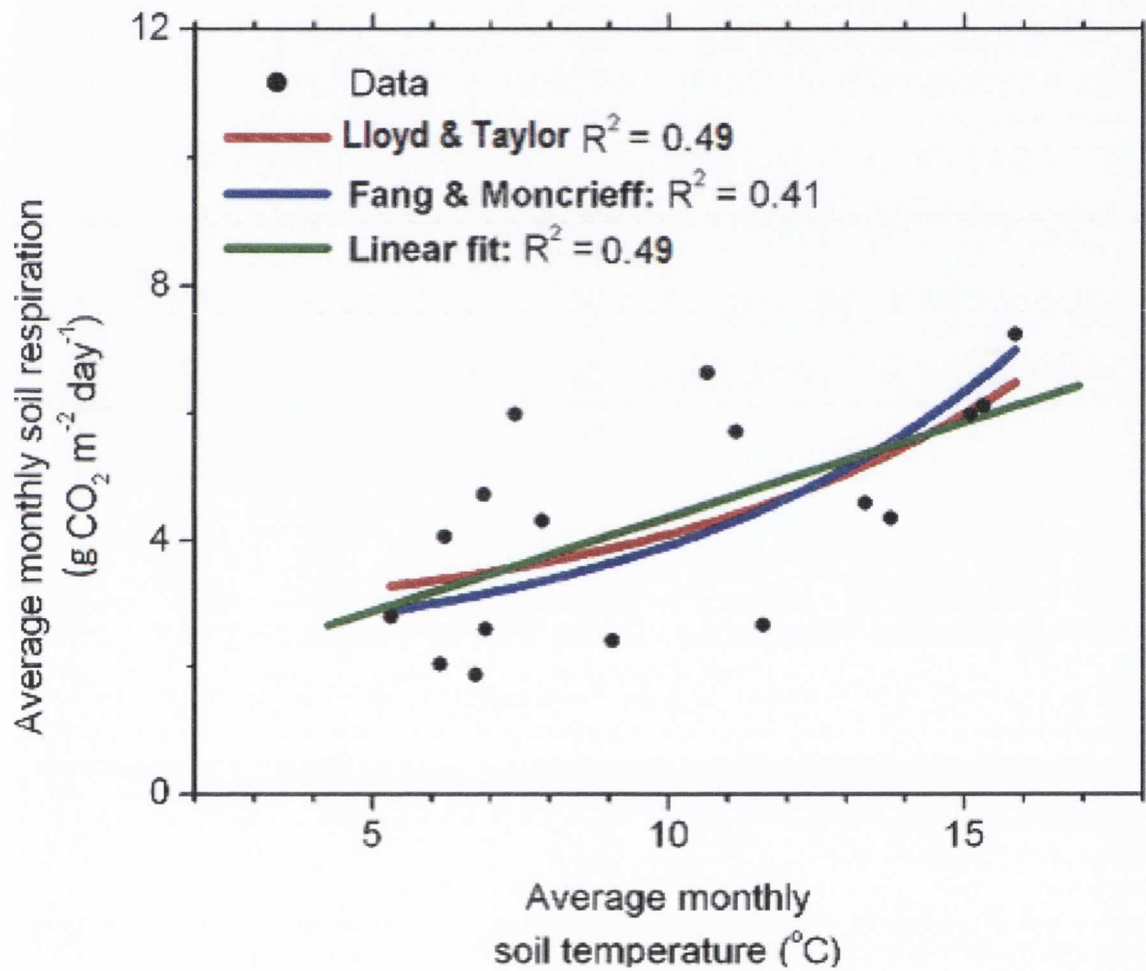


Figure 4.5: Comparing the fit of Q10 models Lloyd and Taylor (1994) and Fang and Moncrieff (2001) with a linear fit of average monthly soil respiration ($\text{g CO}_2 \text{ m}^{-2} \text{ day}^{-1}$) and monthly soil temperature ($^{\circ}\text{C}$) data.

The soil moisture content readings related to rainfall events. The soil moisture content did not display a close relationship to soil CO_2 production rates ($R^2 = 0.04$) (Figure 4.6). In addition, the Pearson Correlation test for soil respiration and soil moisture content did not yield a significant correlation value (r , 0.24; P value, 0.26). Figure 4.7 shows the weekly mean moisture measurements from the *Miscanthus* stand between the October 23rd 2006 and March 2nd 2008.

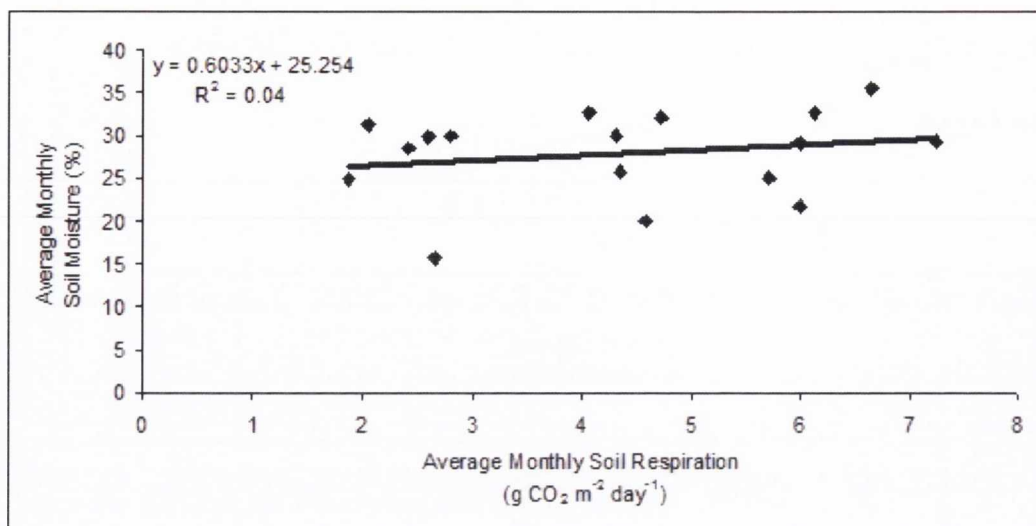


Figure 4.6: The response of average monthly soil respiration (g CO₂ m⁻² day⁻¹) to soil moisture content (%) in the *Miscanthus* stand over 16 months.

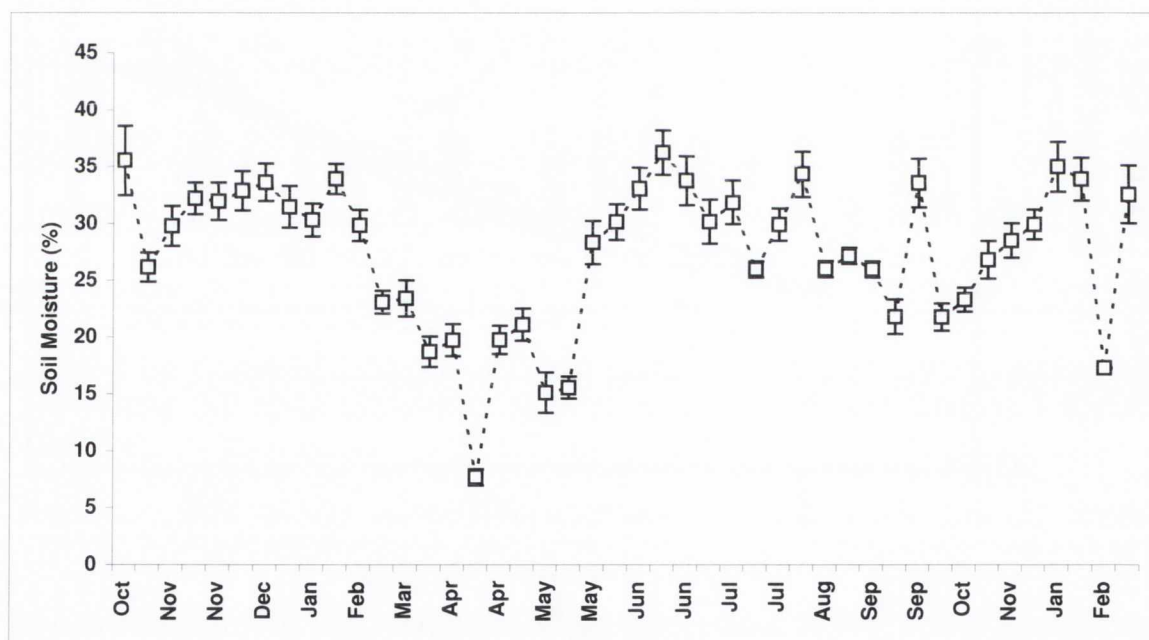


Figure 4.7: Mean soil moisture measurements from 17 sampling sites within the *Miscanthus* stand in Oak Park Research Centre, Co. Carlow, between the 23rd of October 2006 and the 2nd of March 2008. Error bars are $\pm$ standard error.

4.3.3: Leaf Photosynthesis:

The monthly minimum, maximum and mean values of photosynthetic photon flux densities (PPFD) and CO₂ assimilation rates are displayed in Table 4.4. On average, shaded leaves were exposed to 43-59% of the total PPFD levels at the sunlit leaves. In general, PPFD levels during the photosynthesis measurements were low. Highest CO₂ assimilation rates,

Table 4.4: Monthly minimum, maximum and mean values of photosynthetic photon flux density (PPFD) and CO₂ assimilation rates for sunlit and shaded *Miscanthus* leaves from June 28th 2007 to 16th October 2007; carbon equivalent (t C ha⁻¹ yr⁻¹) for the monthly mean CO₂ assimilation rate.

Month	Leaf Position	PPFD ($\mu\text{mol m}^{-2} \text{s}^{-1}$)			CO ₂ assimilation rate ($\mu\text{mol CO}_2 \text{m}^{-2} \text{s}^{-1}$)			t C ha ⁻¹ yr ⁻¹
		Min.	Max.	Mean	Min.	Max.	Mean	
June	Sunlit	134	1005.5	279.5	0.86	11.85	3.98	15.06
	Shaded	-	-	-	-	-	-	-
July	Sunlit	10	1991	504.4	-0.85	24.65	7.71	29.18
	Shaded	21	1718	301.5	-1.7	23.26	4.75	17.97
Aug	Sunlit	0	1514	349.7	-0.85	19.49	6.40	24.22
	Shaded	0	505	185	-0.85	12.32	4.34	16.42
Sept	Sunlit	22	730	292.8	0.22	9.32	4.80	18.16
	Shaded	15	450	126.3	-0.86	4.77	1.26	4.76
Oct	Sunlit	28	991	274.4	1.7	9.61	4.17	15.78
	Shaded	20	543	153.6	0.21	3.72	1.76	6.60

levels during the photosynthesis measurements were low. Highest CO₂ assimilation rates, in both sunlit and shaded leaves, were recorded in July, corresponding to highest PPFD levels. Lowest CO₂ assimilation rates were observed in October in sunlit leaves and in September in shaded leaves relating to lowest PPFD levels. By October 16th the majority of *Miscanthus* leaves had begun to senesce and the measurements were stopped. Diurnal leaf chamber measurements were carried out, on all leaves present on five *Miscanthus* plants, between the 11th and 12th of August (Figure 4.8). The average CO₂ assimilation rate during daylight hours (before 22:00 and after 5.30) was 7.861 $\mu\text{mol CO}_2 \text{m}^{-2} \text{s}^{-1}$ and during night-time hours (22:00 to 5:30) was -0.3778 $\mu\text{mol CO}_2 \text{m}^{-2} \text{s}^{-1}$. The negative sign represents a net release of CO₂ from the leaves (net respiration). The mean and maximum PPFD for the day were 388 and 1389 $\mu\text{mol m}^{-2} \text{s}^{-1}$. Net respiration was equivalent to 21.8% of the total daily net photosynthesis.

To describe the response of CO₂ assimilation in the *Miscanthus* leaves to variation in PPFD, rectangular hyperbolae, expressed by the quadratic equation of Prioul and Chartier (1977) were fitted to the data. Plots were produced in Photosyn Assistant (Dundee Scientific Ltd., Dundee, Scotland) (Figure 4.9 and 4.10); the corresponding Amax (maximum CO₂ assimilation rate) and Φ (quantum efficiency) are presented in Table 4.5.

Table 4.5: Amax and quantum efficiencies for sunlit and shaded *Miscanthus* leaves from June 28th 2007 to 26th September 2007.

<u>Month</u>	Sunlit Leaves		Shaded Leaves	
	Amax ± SE ($\mu\text{mol CO}_2$ $\text{m}^{-2} \text{s}^{-1}$)	Quantum efficiency (Φ)	Amax ± SE ($\mu\text{mol CO}_2$ $\text{m}^{-2} \text{s}^{-1}$)	Quantum efficiency (Φ)
June	13.2 ± 1.74	0.0193	-	-
July	18.9 ± 0.61	0.0160	18.5 ± 6.2	0.0237
August	19.1 ± 0.56	0.0259	12.5 ± 0.45	0.027
September	10.2 ± 1.65	0.0499		

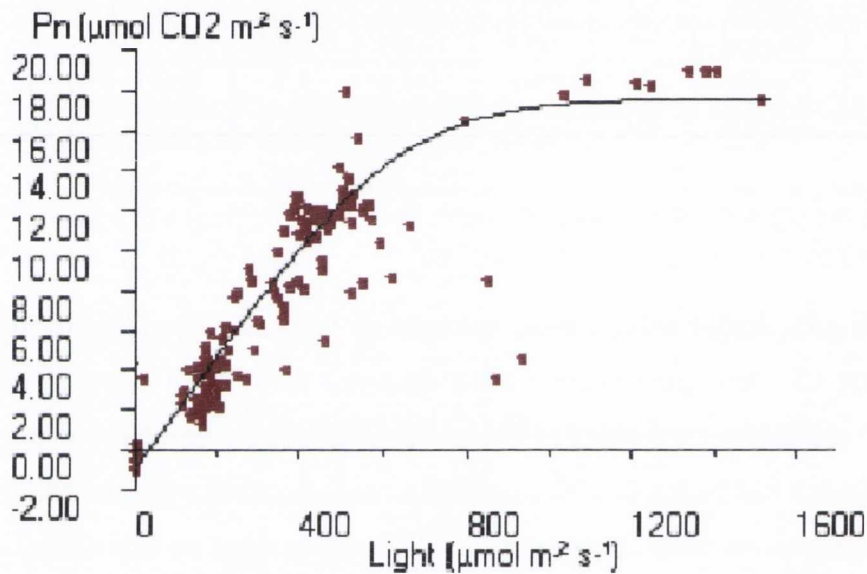
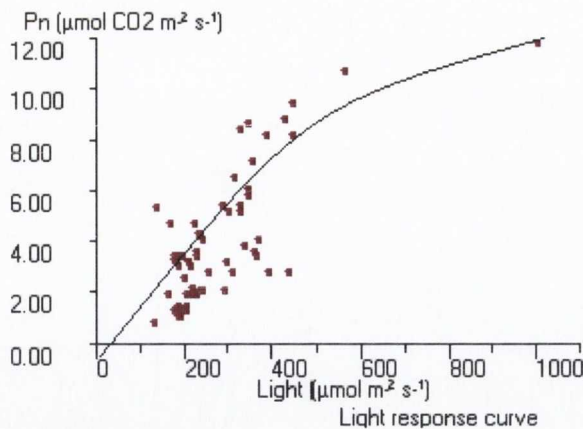


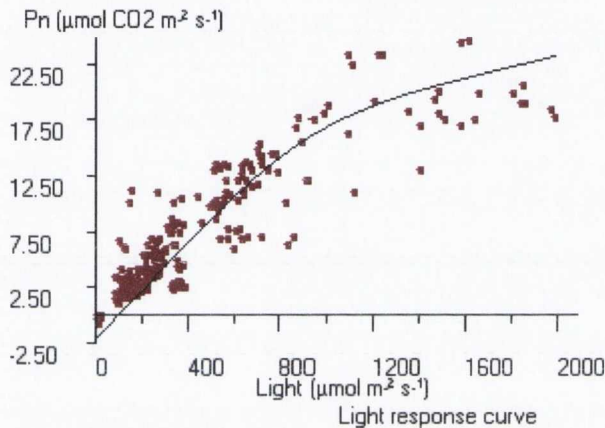
Figure 4.8: Light response curve based on leaf chamber measurements from all leaves present on five *Miscanthus* plants over 24 hours on the 11th-12th of August 2007. The calculated Amax and Φ for the day were 16.8 $\mu\text{mol CO}_2 \text{m}^{-2} \text{s}^{-1}$ and 0.025 respectively.

The *Miscanthus* leaves were exhibiting senescence in the shaded region of the plant in September and in both sunlit and shaded regions of the plant in October. There were insufficient photosynthesis measurements for these leaves to produce light response curves.

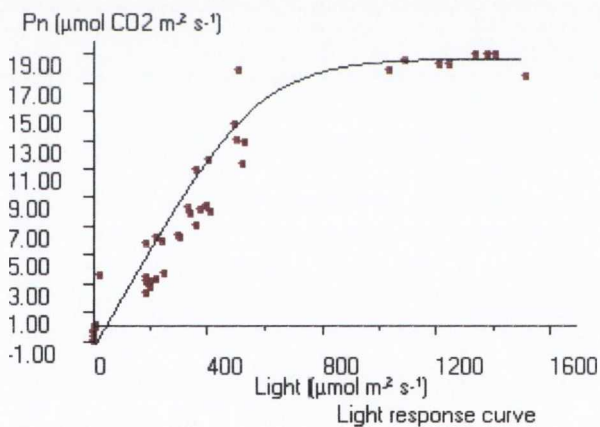
June



July



Aug



Sept

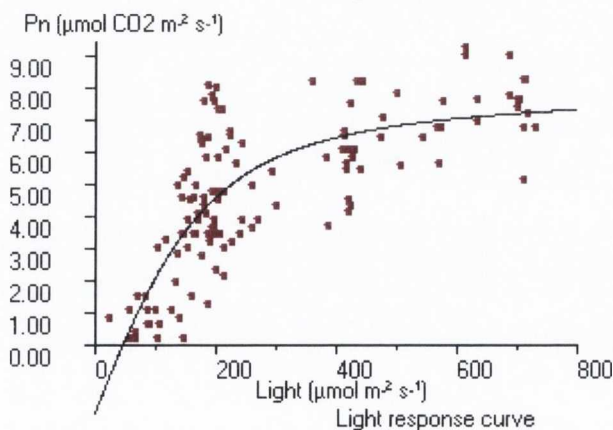
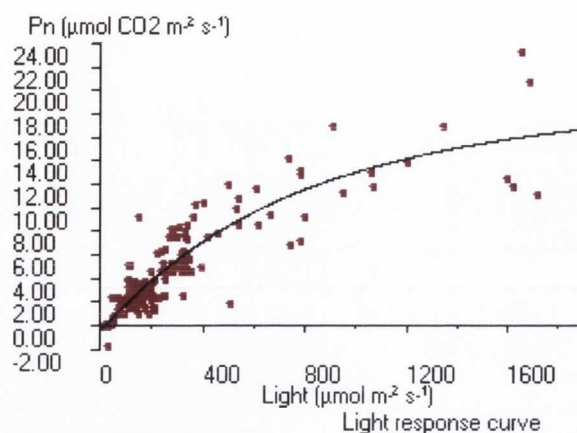


Figure 4.9: Light response curves for sunlit *Miscanthus* leaves based on weekly leaf chamber measurements from June to September 2007

July



Aug

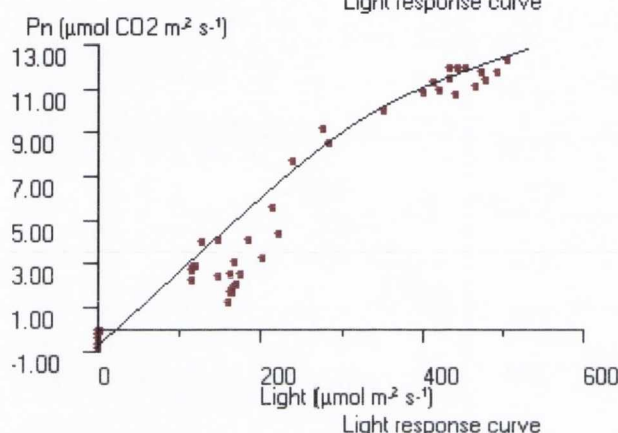


Figure 4.10: Light response curves for shaded *Miscanthus* leaves based on weekly leaf chamber measurements from July and August 2007.

4.4: Discussion:

Chamber measurements are regularly employed for measuring carbon fluxes within ecosystems. Chambers allow for the measurement of fluxes over specific sampling areas. Corresponding environmental conditions can also be recorded, thereby allowing for the development of possible correlations between fluxes and environmental variables. This chapter was specifically concerned with determining soil respiration and leaf chamber photosynthesis for the *Miscanthus* crop.

4.4.1: Soil Analysis:

The heterogeneity of soil can lead to a high level of spatial variation in soil effluxes; quantifying soil properties is important due to their impact on carbon cycling in the soil (Kimball 1983; Kimball and Lemon, 1971). Oak Park Research Centre is located in the Barrow Valley, the floor of which comprises of an extensive carboniferous limestone formation with earthy limestone at the base, dolomites and oolites above and finally, fairly pure limestone (Conry and Ryan 1967). During the 'Weichsel Glaciation', the last glaciation episode, fluvial-glacial gravel and sand derived from carboniferous limestone

was deposited over the area where Oak Park is now situated (Conry and Ryan, 1967); forming part of a 10-25 m thick karstified aquifer (Gardiner and Ryan, 1969).

The soil at the Oak Park site, to a depth of 35 cm, was described as a ‘Sandy-Loam’, using a standard USDA textural triangle. The high sand content of the soil meant it was a lighter soil; this is beneficial for *Miscanthus* growth, as it tends to retain heat longer than heavier soils. Furthermore, the lower clay content ensures that the site does not get excessively water logged, which is an important consideration for farm machinery during harvest times.

A soil pH test was carried out to determine whether the *Miscanthus* stand is growing in favourable growth conditions. The pH of the soil ranged from 7.26 ± 0.08 to 7.47 ± 0.02 . *Miscanthus* is tolerant to a wide range of pH values, but the optimum range is 5.5 to 7.5 (Finch *et al.*, 2009). The Oak Park site falls in the upper limit of the optimum range. The soil became more acidic with depth. This was also seen in a neighbouring *Miscanthus* field with pH values of 5.9 ± 0.01 at 10-20 cm and 6.3 ± 0.08 at 40-50 cm (Albanito, 2009). The difference in pH values between the two sites is likely due to differences in past vegetation covers and management activities.

The Oak Park site had an average LOI % of 6.58 ± 1.01 . A LOI of 0-10% has been reported as the normal range for the majority of UK (Carey *et al.*, 2008). No such national soil maps, showing average LOI %, are currently available for Ireland. As expected, the gravimetric water content of the soil decreased with depth, from $28.13\% \pm 1.61$ at 0-5 cm to $23.24\% \pm 1.85$ at 40-45 cm. It is important to note that water content shows seasonal variation and so these data only describes the conditions in the soil samples at the time of sampling (November 2008). *Miscanthus* grows on most soils, but does favour ones with a high water-holding capacity (Christian and Haase, 2001). Too much water reduces air movement through the soil; too little water held in the soil will lead to drought conditions for the crop.

Bulk density is a measure of the dry weight of soil per unit volume; it indicates the degree of soil compaction, a significant factor in root growth, root penetration and the movement of water and gases. Bulk density was an important test in this project as the movement of CO₂ in the soil occurs through this network of air or water filled pore spaces (Simunek and Suarez, 1993). The bulk density results showed an increase with depth, as is commonly reported in the literature. Sub-surface layers are subject to greater compaction, have greater

root penetration and reduced organic matter aggregation which reduce pore spaces thus increasing bulk density values (Lampurlanès and Cantero-Martinez, 2003; McNabb *et al.*, 2001). The Oak Park site results are comparable with those from the neighbouring *Miscanthus* field: Oak Park site ($0.85 \pm 0.03 \text{ g cm}^{-3}$ to $1.13 \pm 0.01 \text{ g cm}^{-3}$ for 0-5 cm and 40-45 cm respectively) and neighbouring *Miscanthus* site ($1.07 \pm 0.05 \text{ g cm}^{-3}$ to $1.31 \pm 0.05 \text{ g cm}^{-3}$ for 0-10 cm and 40-50 cm respectively). The bulk density results suggest the soil is quite porous, and so should allow free gaseous exchange. This is an important quality when considering the movement of CO_2 in soil respiration and net ecosystem exchange measurements.

4.4.2: Soil Respiration:

The spatial and seasonal changes in soil CO_2 fluxes were obtained by carrying out regular measurements at 17 locations within the *Miscanthus* stand over 16 months. A large degree of spatial variation was seen in the soil respiration measurements. The average co-efficient of variation for the experimental period was 34% but was markedly lower during the growing season (19%). Flanagan and Johnson (2005) reported similar CV values (18%) between respiration fluxes from 6 replicate chambers; they suggested that a CV of 18% reflected adequate sampling to characterise seasonal variation. Spatial heterogeneity in soil respiration fluxes is common; Davidson *et al.* (1998) demonstrated that landscape heterogeneity has a strong influence on CO_2 production. In addition, differing root densities, soil organic matter contents, C:N ratios, C:Lignin ratios, soil textures or soil acidities all affect individual sampling site respiration rates.

The soil respiration rates from the *Miscanthus* site were compared to rates measured by Albanito (2009) in a neighbouring *Miscanthus* stand (Table 4.3). In general, a greater range of respiration rates, were recorded in the neighbouring site ($0\text{-}27 \text{ g CO}_2 \text{ m}^{-2} \text{ day}^{-1}$) compared to the study site ($0.52\text{ to }10.55 \text{ g CO}_2 \text{ m}^{-2} \text{ day}^{-1}$). Both displayed similar patterns of respiration with maximum rates in the summer months and lowest rates in the winter. However, Albanito (2009) reported considerably greater respiration rates in the summer and autumn periods. There are several possible reasons for these differences: the neighbouring *Miscanthus* stand was a younger crop and so may have been more productive, the soils were subjected to different previous vegetation types (forest compared to arable crops), and also the respiration rates on the two sites were measured using different methodologies. Soil respiration has been previously measured on *Miscanthus sinensis* (a close relative of *Miscanthus*) in Japan (Yazaki *et al.*, 2004; Saito, 1975).

Respiration rates at the Oak Park site were comparable with the lower end of the reported *Miscanthus sinensis* range by Saito (1975) ($4.58 - 21.33 \text{ g CO}_2 \text{ m}^{-2} \text{ day}^{-1}$). Substantially larger rates ($38.65 - 42.53 \text{ g CO}_2 \text{ m}^{-2} \text{ day}^{-1}$) were measured by Yazaki *et al.* (2004); these rates were three times greater than the maximum respiration rate recorded at the Oak Park site. Based on these findings, *Miscanthus sinensis* stands appear to have larger soil respiration rates than *Miscanthus x giganteus* stands, although direct comparisons are difficult due to the large differences in environmental, climatic and edaphic conditions.

Soil temperature did not exhibit spatial variation whilst soil respiration did, suggesting that temperature alone was not the main driver in respiration rates. Nonetheless, temperature did account for approximately 49% of the variation, a similar percentage was reported by Albanito (2009) ($R^2 = 0.51$). In a study of soil respiration from a mixed plantation of C4 tall grasses soil temperature accounted for between 40 to 70% of the variation in respiration rates. The expression of temperature as described by Q10 models did not improve the correlation (Figure 4.5). Many studies have shown that temperature alone does not fully explain soil respiration rates namely because the multiple components of soil have different temperature sensitivities (Gu *et al.*, 2004; Lenton and Huntingford, 2003). Janssens *et al.* (2001) reviewed CO_2 flux data from 18 forest sites in the EUROFLUX project and reported no significant correlations between soil respiration and temperature.

Usually soil moisture is the other dominant variable controlling soil respiration (Davidson *et al.*, 1998). At the *Miscanthus* stand soil moisture content did not correlate well with the soil CO_2 effluxes ($R^2 = 0.04$). Again, a similar result was reported by Albanito (2009) ($R^2 = 0.08$). Longdoz *et al.* (2000) detailed a lack of response between soil respiration and soil water content at two forest sites. As soil temperature and moisture only described approximately half the variation in soil respiration rates, other factors must be involved. It has been argued that by relating respiration to productivity, important factors such as soil fertility, site history and vegetation cover are considered. This is investigated in Chapter 5.

4.4.3: Leaf Photosynthesis:

Leaf photosynthesis measurements were made under ambient conditions on sunlit and shaded leaves to investigate the pattern of carbon fluxes at different locations over the day. The main disadvantage of measuring leaf photosynthesis in field conditions is the low light levels. At the Oak Park site the mean PPFD during chamber measurements was $340 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ at sunlit leaves and $191 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ at 1m depths in the canopy. Generally, in photosynthesis studies, lower PPFD are avoided to prevent the Kok effect,

which steepens the lowest section of the light response curves (Sharp *et al.*, 1984). Nonetheless, Long *et al.* (1994) suggested that in mature canopies with large LAI, like that of *Miscanthus*, CO₂ assimilation may be as much determined by capacity for light limited photosynthesis as by light saturated assimilation rates. Dohleman and Long (2009) reported that under field conditions, significant amounts of carbon assimilation in *Miscanthus* occur under non-light saturation conditions, emphasizing the importance of quantifying photosynthetic rates under natural ambient conditions. Non-light saturating conditions are common on overcast days, at dawn and dusk and when leaves overshadow other leaves.

Carbon assimilation was highest at full leaf expansion and decreased with canopy depth as the leaves became shaded by newly developing leaves; similar results are described by Kikuzama (2003). In addition, Kromdijk *et al.* (2008) have shown that CO₂ leakage from bundle sheath increases with depth into the canopy; thereby reducing the quantum efficiency of the lower leaves and lessening CO₂ assimilation. The *Miscanthus* leaves exhibited relatively low Φ values (0.002 to 0.049). Ehleringer and Pearcy (1983) suggest a quantum efficiency value of 0.065 for leaves of NADP-ME C₄ grasses. Beale *et al.* (1996) reported a range of 0.045-0.074 from a three-year-old *Miscanthus* stand in Essex, England, under light saturation conditions ($>1400 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$). The *Miscanthus* stand never achieved the ideal Ehleringer and Pearcy (1983) value and its maximum Φ value was on the lower end of the Beale *et al.* (1996) range. The lower Φ levels may be attributed to the health and age of the stand. A slightly higher maximum Φ value of 0.055 was reported by Ms Caroline Hayes in her M.Sc. project, when measuring photosynthetic rates of the *Miscanthus* leaves at the study site under artificial light levels (0 to $2000 \mu\text{mol m}^{-2} \text{ s}^{-1}$) (Figure 4.11). Even at the higher artificial light levels the *Miscanthus* leaves did not exhibit light saturation. The photosynthetic rates from the sunlit leaves in July (Figure 4.9) closely resemble those recorded under the artificial light conditions (Figure 4.11) because ambient light levels reached $1991 \mu\text{mol m}^{-2} \text{ s}^{-1}$. Li *et al.* (2003) also found that light saturation was not achieved up to a PPFD of $2000 \mu\text{mol m}^{-2} \text{ s}^{-1}$ in a mixed *Miscanthus* grassland in Japan.

Typical midday CO₂ assimilation rates at the Oak Park site were 4 to $6 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ (June to October) while at the Essex site the typical midday range was 20-27 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ (Beale *et al.*, 1996). In ambient field conditions, in Midwestern America, Dohleman and Long (2009) measured photosynthesis in sunlit and shaded leaves; averaging 17.2 and $4.20 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ respectively. Much lower rates were recorded at the Oak Park site:

5.4 and 3.03 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$. The published works suggest *Miscanthus* is capable of achieving significantly higher photosynthetic rates than were recorded during this study. The low light levels are the most likely cause but the age of the crop may be a factor worthy of consideration, as most studies are performed on newly established plots. An interesting future experiment would be to carry out controlled environment photosynthesis measurements on leaves within the canopy over a number of years to determine the effect of plant age on Φ . As the leaf environment was not constant in this experiment direct comparisons between leaves could not be performed.

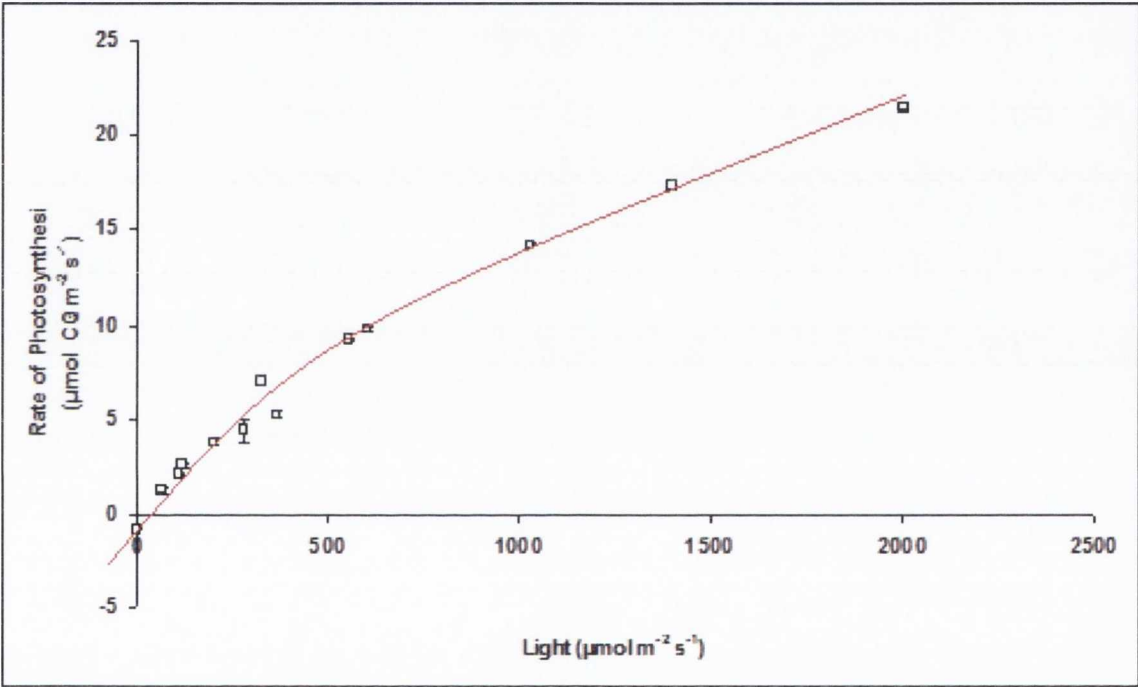


Figure 4.11: Light response curve for sunlit *Miscanthus* leaves in August 2007 based on leaf chamber measurements with an artificial light source (0 to 2000 $\mu \text{ mol m}^{-2} \text{ s}^{-1}$). Data from Ms Caroline Hayes (M.Sc. Project).

Based on findings in the literature *Miscanthus* is capable of photosynthesising at greater rates than was seen during this experiment (Naidu and Long, 2004; Farage *et al.*, 2006; Wang *et al.*, 2008). Greater photosynthesis rates yield higher biomasses; the low PPFD levels at the Oak Park site are a likely contributing factor in the low harvested yields (5.15 to 10.17 t DM ha⁻¹) compared to reported yield ranges from 5 to 55 t DM ha⁻¹ (Heaton *et al.*, 2010). It is recommended that PPFD levels during the growing season are considered before any location is decided on for planting new *Miscanthus* stands in order to maximise yields and increase the carbon sink strength of the crop.

4.5: Summary:

- The soil under the *Miscanthus* stand was classified as a grey-brown podzolic soil type with a profile contained an O horizon (0-3 cm) of leaf litter and plant residue, an A horizon (3-35 cm) of sandy loam and a Bh horizon (35-80 cm).
- The pH of the soil ranged from 7.26 ± 0.08 to 7.47 ± 0.02 . The average LOI % was 6.58 ± 1.01 . The bulk density results suggest the soil is quite porous and so should allow free gaseous exchange (0.85 to 1.13 g cm^{-3}).
- The annual mean soil respiration rate for the *Miscanthus* stand was calculated as $6.59 \text{ g CO}_2 \text{ m}^{-2} \text{ day}^{-1}$. Maximum soil respiration rates were recorded in the summer months ($10.55 \text{ g CO}_2 \text{ m}^{-2} \text{ day}^{-1}$) and minimum values were seen in the winter months ($0.52 \text{ g CO}_2 \text{ m}^{-2} \text{ day}^{-1}$).
- Pearson Correlation tests indicated that soil respiration and soil temperature had an intermediate strength correlation ($r=0.451$; $P=0.002$); while soil respiration and soil moisture were not significantly correlated ($r, 0.243$; P value, 0.265).
- Within a *Miscanthus* canopy, shaded leaves (1m below the most recent fully expanded leaf) were, on average, only exposed to 43-59% of the total PPFD levels above the canopy.
- Typical midday CO_2 assimilation rates at the Oak Park site were 4 to $6 \text{ } \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ (June to October) with highest CO_2 assimilation rates in both sunlit and shaded leaves recorded in July
- The *Miscanthus* leaves exhibited relatively low Φ values (0.002 to 0.049) and light saturation was not achieved up to a PPFD of $1991 \text{ } \mu\text{mol m}^{-2} \text{ s}^{-1}$.

Chapter 5

General Discussion

5.1: Summary and Synthesis:

This study focused primarily on the potential to mitigate atmospheric CO₂ emissions through soil organic carbon sequestration, in the bioenergy crop *Miscanthus x giganteus*. The goal was to determine if deployment of the crop was an effective strategy in reducing Ireland's CO₂ emissions and meeting policy commitments. A further objective was to provide improved estimates, based on micrometeorological and inventory methods, of above ground, below ground, litter and soil carbon stocks.

Under Article 3.4 UNFCCC, countries can count sequestration as a contribution to decreasing GHGs (IPCC, 2001). This has driven research into improving the current understanding of the processes regulating carbon sequestration (Jones and Donnelly, 2004). Bioenergy crops have the potential to mitigate substantial quantities of carbon but the rates of sequestration depend strongly on land use history, soil type, harvesting cycles and other management practices (Sartori *et al.*, 2006). The soil organic pool tends to be enhanced under more deeply rooted perennial grasses such as *Miscanthus*. In an Irish context, Dondini *et al.* (2009) demonstrated that *Miscanthus* increases soil carbon storage by between 2 and 3 t C ha⁻¹ y⁻¹ when it is planted on arable land.

The use of bioenergy crops for electricity generation is considered an effective means of mitigating the greenhouse effect through fossil fuel substitution (Lettens *et al.*, 2003) and by the net sequestration of atmospheric carbon into soil organic carbon (Sartori *et al.*, 2006). Fuels derived from bioenergy crops can theoretically provide an energy source with near zero carbon additions into the atmosphere as the carbon released upon combustion is recaptured via photosynthesis over the following growing season. No alternative energy source provides the combined benefits of sequestering atmospheric carbon and reducing fossil carbon release (Sims *et al.*, 2006). Cannell (2003) suggested that 1 t DM used for electricity generation prevents 0.5 t C being emitted from coal in electricity generation. *Miscanthus* has a gross calorific value of 17 MJ kg⁻¹ DM, similar to that of other woody materials (McKervey *et al.*, 2008). Based on the harvest data from Oak Park, one hectare of *Miscanthus* would contain 176 GJ of energy, which is the equivalent of 4.06 t of coal or 50,700 kWh of electricity. In addition, Styles and Jones (2007) have estimated that in a scenario where *Miscanthus* plantations replace tillage land for a century, the annual soil

carbon sequestration effect surpasses the CO₂ equivalent emissions arising from the entire electricity fuel chain.

The extent to which an energy crop can impact the global carbon cycle depends on the net carbon emissions and relative efficiency of overall biomass production and utilization. Calculating the carbon mitigation potential of energy crops is not straightforward (Clifton Brown *et al.*, 2004). Carbon emitted during crop management and transport must be accounted for and the amount of mitigation depends on whether calculations are performed for the primary or end user.

5.1.1: Aims:

The aim of this chapter is to compare and summarise the information presented in the previous chapters and construct a carbon cycle for the *Miscanthus* stand under investigation. Future potential studies will be discussed and conclusions will be drawn.

5.1.2: Comparing Chamber and Eddy Covariance Fluxes:

Comparisons of eddy covariance (Chapter 3) and chamber-based (Chapter 4) measurements of NEE can be performed by comparing EC measurements with estimated rates calculated by scaling up component fluxes (Goulden *et al.*, 1996; Law *et al.*, 1999; Tang *et al.*, 2008). In theory, subtracting scaled-up soil chamber respiration rates from total ecosystem respiration (TER) fluxes, determined by eddy covariance, yields total stand respiration. In order to estimate the annual production of CO₂ from the soil temperature response Q10 models are usually used; however, as shown in Chapters 3 and 4, soil temperature did not show a strong correlation with respiration. Soil temperature accounted for approximately 40-53% of the variation in respiration rates. Temperature models assume the effects of other variables on soil respiration are limited, and as this was not clearly the case for the *Miscanthus* stand an alternative approach was developed. Cumulative fluxes were interpolated based on a linear change in rates between measurement periods. Large errors are associated with this method of calculating rates; however, the reasonably short intervals between measurements (average 7 to 10 days) go some way towards validating the approach. Figure 5.1 shows the cumulative soil respiration flux, as calculated based on chamber measurements, over 16 months and the corresponding cumulative total ecosystem (TER) fluxes from the eddy covariance measurements. Over the 16 months, the soil at the *Miscanthus* site respired 569.66 g C m⁻², which was 48.99% of the TER. Data are usually reported on an annual basis so the soil respiration flux from October 2006 to 2007 was

calculated. Over this period $510.45 \text{ g C m}^{-2}$ was respired from the soil in the *Miscanthus* stand, representing 60.25% of the TER fluxes. The remaining 39.75% must therefore relate to plant and litter respiration. Large variations in annual soil respiration rates have been recorded around the world (Table 5.1). Soil respiration at the *Miscanthus* site was most similar to respiration fluxes recorded in crop and field-type vegetations ($544 \pm 80 \text{ g C m}^{-2} \text{ yr}^{-1}$) (Raich and Schlesinger, 1992) and soil respiration at a *Fagus sylvatica* forest ($460 \text{ g C m}^{-2} \text{ yr}^{-1}$) (Janssens *et al.*, 2001). The range of soil:TER percentages reported in the literature is as broad, 41-138.2%. The *Miscanthus* value of 60.25% was very similar to 63.2% from a broad-leaved secondary forest (Miyama *et al.*, 2005). Direct comparisons are difficult to perform as differences in vegetation types, locations and climates all have strong influences on respiration rates. However, it can be concluded that 60.25% falls well within the published range and that nearly two-thirds of respiration at the *Miscanthus* stand is derived from the soil.

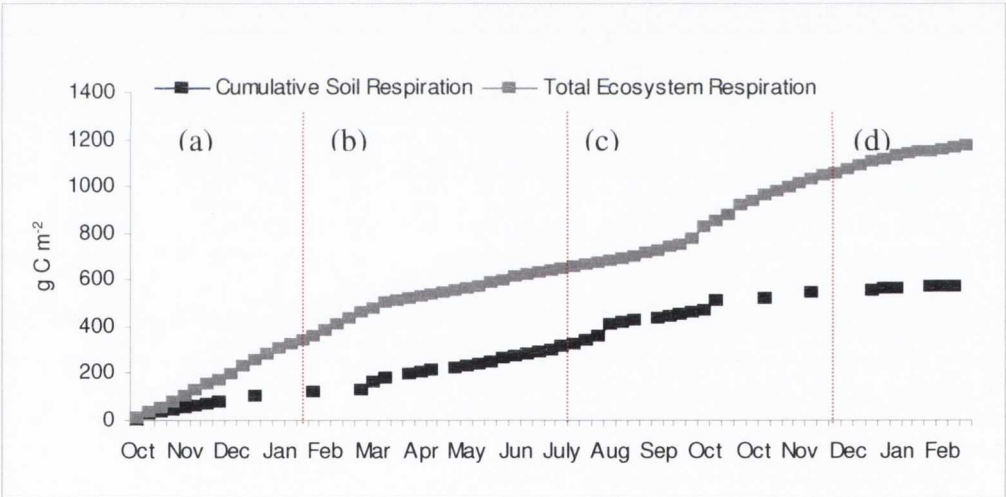


Figure 5.1: Cumulative soil respiration flux from scaled up chamber measurements during the Senescence and Litter Fall (2006/07) (a), Early Growth (b), Maximum growth (c), and senescence and litter fall (2007/08) (d) periods. Also showing the cumulative total ecosystem respiration fluxes from the eddy covariance study.

Table 5.1: Annual soil respiration rates and soil/TER percentages from a variety of vegetation types

Vegetation Type	Soil Respiration (g C m⁻² yr⁻¹)	Soil/TER (%)	Reference
Fir Forest	58.4		Raich and Tufekcioglu (2000)
Fagus sylvatica	460	41.6	Janssens <i>et al.</i> (2001)
Crops and fields	544		Raich & Schlesinger (1992)
<i>Picea abies</i> and <i>Pinus sylvatica</i>	709		Janssens <i>et al.</i> (2001)
Soybean	750	51.6	Tufekcioglu <i>et al.</i> (2000)
Beech Forest	870		Longdoz <i>et al.</i> (2000)
Poplar	1140	92	Tufekcioglu <i>et al.</i> (2000)
Tropical Moist Forest	1260		Raich & Schlesinger (1992)
Cassava	1262.9		Raich <i>et al.</i> (1985)
Switchgrass	1383.4		Tufekcioglu <i>et al.</i> (2000)
Fallow field	1898		Raich & Tufekcioglu (2000)
Broad leaf forest	2503	63.2	Miyama <i>et al.</i> (2005)

Insight into night-time leaf respiration in the *Miscanthus* canopy was obtained from the diurnal set of CO₂ measurements carried out on August 11th 2007 (Chapter 4). The average CO₂ released from the leaves during the night-time hours was 0.3778 µmol CO₂ m⁻² s⁻¹. The night-time fluxes were much smaller than daytime fluxes (approximately 4%). To allow for comparisons with the EC fluxes the leaf respiration data were multiplied by the average LAI of the canopy. An average LAI of 5.8 was calculated for August 2007 based on measurements detailed in Chapter 2. Canopy respiration was estimated as 2.12 µmol CO₂ m⁻² s⁻¹ for the night of August 11th. Night-time EC fluxes for the same night yielded an average flux of 3.92 µmol CO₂ m⁻² s⁻¹. This suggests that the 54% of the night-time respiration originated from leaf material and the other 46% must be derived from stem, litter and soil respiration. By scaling up the chamber measurements it was calculated that over the measurement night a total of 0.73 g C m⁻² was released from the *Miscanthus* leaves. This analysis provides some interesting information relating to the partitioning of night-time fluxes; however, there is insufficient replication over the growing season to extrapolate the relationship between canopy and total ecosystem respiration.

Unfortunately, scaling up leaf level photosynthesis measurements is not straightforward. Scaling up rates based on LAI assumes that the photosynthetic rate at the leaf level is the same as at the canopy level. This is clearly not the case in *Miscanthus* where individual leaves are exposed to markedly different light conditions and are at different stages in their life cycle. The leaf level photosynthesis measurements in Chapter 4 showed a distinct difference between sunlit and shaded leaves on the same plant. It was therefore deemed that scaling up leaf-level chambers would yield erroneous estimates of daytime NEE fluxes.

5.1.3: Fluxes and Crop Productivity:

As soil temperature and moisture content described only approximately 50% of the variation in soil respiration rates (Chapter 4), other factors must be involved. Lyr and Hoffman (1967) suggested that soil respiration originates primarily from plant roots and microbial activity; the increase in respiration rates with temperature is a response of increased root biomass in warmer months. Root respiration is constrained by gross primary productivity (GPP) and so by association GPP can explain changes in the autotrophic proportion of soil respiration (Janssens *et al.*, 2001). Extending this theory further, the production of greater substrate through GPP can be related to higher levels of heterotrophic respiration, predominately, through the decomposition of leaf litter and fine roots. A positive correlation between soil respiration and GPP was observed among several EUROFLUX sites ($r = 0.76$, $n = 8$, $P \text{ value} = 0.048$) (Janssen *et al.*, 2001). It has been argued that by relating respiration to productivity, important factors such as soil fertility, site history and vegetation cover are considered.

The potential relationship between soil respiration rates and biomass in the *Miscanthus* stand was investigated (Figure 5.2). Average monthly harvested biomass (calculated from data presented in Chapter 2) and average monthly soil respiration rates were not directly correlated ($r = 0.14$, $P \text{ value} = 0.604$) but the respiration data did display the same pattern as biomass two-months in advance ($r = 0.60$, $P \text{ value} = 0.017$). For instance, highest values of respiration and biomass measurements were recorded in July and September, whilst lowest values were in February and April, respectively. As a *Miscanthus* stand is characterised by a substantial litter fall period (December to January) this factor was also considered (Figure 5.3). Leaf litter provides a large amount of organic matter, which available for heterotrophic respiration. From October to December the decrease in soil respiration may be attributed to the senescence of the crop and the associated decline in

photosynthesis. The increase in average respiration in January may be due to litter shedding, providing a substantial pool of organic matter for heterotrophic respiration. Plant detritus is closely related to soil respiration, with respiration rates increasing with the amount of litter production (Maier and Kress, 2000). Following the exponential decay model for litter decomposition described in Chapter 2, an initial burst in decomposition occurs in the first month (January) as labile carbon is respired, followed by a lull (February) and then an exponential increase in decomposition for approximately 1.7 years (20 months) as the recalcitrant carbon becomes more available. This may go some way towards explaining the increasing soil respiration rates in late spring and early summer. In addition, the substantial harvest residue left on the field after the crop was harvested in April also provided a source of readily respired carbon. Maximum soil respiration rates occurred two months before peak standing biomass. At this stage the *Miscanthus* canopy was rapidly developing and leaf litter was abundant. Raich and Tufekcioglu (2000) also reported high soil respiration rates under dense canopies with substantial plant residue. As expected, soil respiration rates decreased following the senescent period of the crop, as the amount of CO₂ entering the system through photosynthesis was negligible.

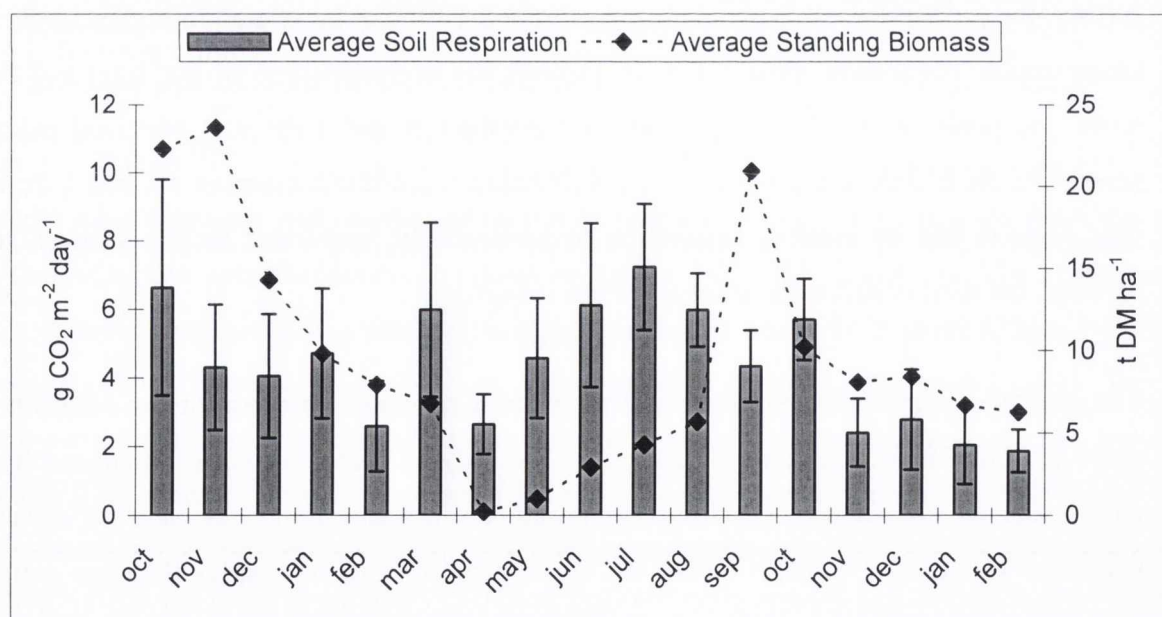


Figure 5.2: Average monthly soil respiration (g CO₂ m⁻² day⁻¹) and average monthly dry weight standing biomass (leaves and stems) (t DM ha⁻¹) in the *Miscanthus* stand over 16 months. Error bars represent ± standard deviation.

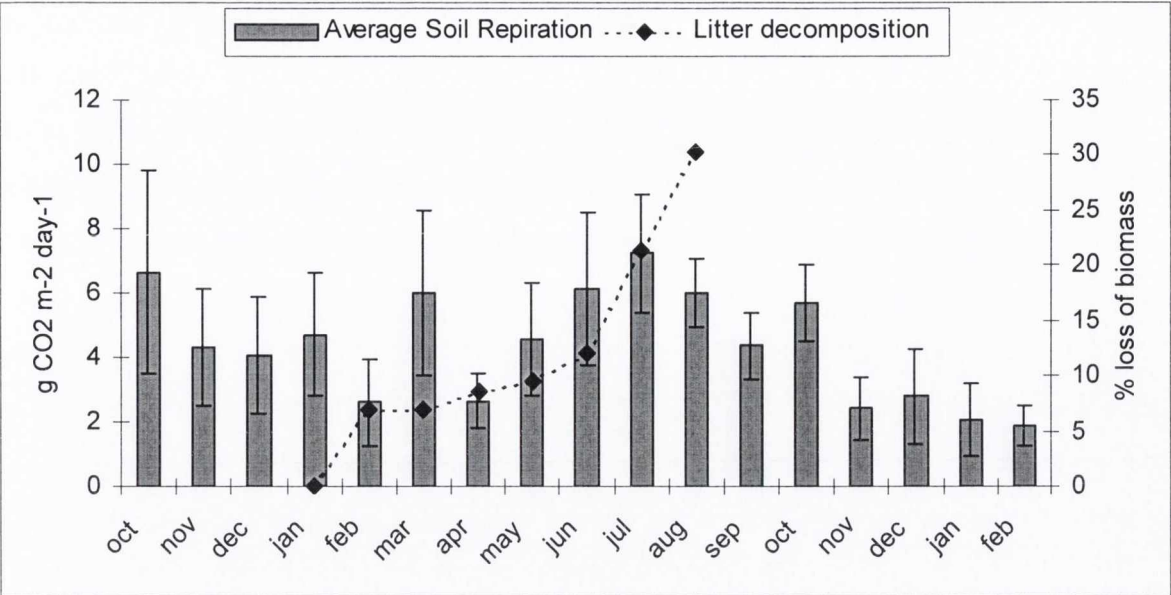


Figure 5.3: Average monthly soil respiration rates (g CO₂ m⁻² day⁻¹) with leaf litter decomposition based on the model derived in Chapter 2. Error bars represent ± standard deviation.

5.1.4: Net Biomass Production (NBP):

Net Biomass Production is the sum of NEE minus carbon losses through harvesting, herbivory or fire. At the Oak Park site neither herbivory or fire are factors, so in this situation:

$$NBP = NEE - \text{harvested material}$$

In the *Miscanthus* stand NBP denotes the amount of carbon that remains in a field annually after the above ground biomass is harvested. It should be noted that fallen leaf litter is not included in the harvested material. The litter is subject to decomposition and is accounted for in the R_{eco} fluxes. The average standing biomass at the *Miscanthus* site at the time of harvest was 6.75 t DM ha⁻¹ in 2008 (Chapter 2). Harvey (2007) reported that 47% of *Miscanthus* dry matter is carbon; therefore, the biomass at the time of harvest had a carbon equivalent of 3.17 t C ha⁻¹. This value was also used to represent the harvested material in 2009 as no biomass measurements were for this period. The NBP was calculated as follows:

$$\begin{aligned} \text{Year 1:} \quad NBP &= (2.7 \text{ t C ha}^{-1}) - (3.17 \text{ t C ha}^{-1}) = -0.47 \text{ t C ha}^{-1} \\ \text{Year 2:} \quad NBP &= (3.9 \text{ t C ha}^{-1}) - (3.17 \text{ t C ha}^{-1}) = 0.73 \text{ t C ha}^{-1} \end{aligned}$$

These data indicate that the *Miscanthus* stand was a NBP source of carbon in Year 1 and a net sink in Year 2. The Year 2 data indicate that the *Miscanthus* stand was better than

carbon neutral, even factoring in the release of carbon stored in the biomass upon combustion. This suggests that 0.73 t C ha^{-1} was sequestered into the underlying soil and below-ground biomass structures. Using the Matthews and Grogan (2001) model, Clifton Brown *et al.* (2001) predicted that soil organic carbon (SOC) accumulation rates of $0.86 \text{ t C ha}^{-1} \text{ yr}^{-1}$ could be expected under Irish *Miscanthus* plantations on previously tilled soils.

The predominant difference between the two measurement years was eight months of lower R_{eco} fluxes in Year 2 compared to Year 1. Studies have indicated that shifts in respiration can be the dominant control on interannual variation in the net carbon sink-source status of an ecosystem (Valenti *et al.*, 2000; Saleska *et al.*, 2003; Griffis *et al.*, 2004). In this study the lower annual R_{eco} fluxes converted the *Miscanthus* stand from a net source of carbon to a net sink at the NBP level. Factors and management practices that encourage lower ecosystem respiration should be investigated and encouraged in order to improve the potential carbon sink strength of the crop. The weak carbon source in Year 1 and the carbon sink in Year 2 at the *Miscanthus* stand are very favourable outcomes. They suggest that the establishment of *Miscanthus* plantations is an effective strategy in reducing CO_2 emissions in Ireland when planted on previously arable sites.

5.1.5: Carbon Cycle of a *Miscanthus* crop:

The primary aim of this study was to construct a carbon cycle for the energy crop *Miscanthus x giganteus*. EC measurements provide a direct measure of the carbon sequestration potential of an ecosystem and facilitate the development of comprehensive carbon balance models (Figure 5.4). Inventory and biometric measurements are also important in C accounting and provide useful information relating to carbon storage in different pools within the crop (Figure 5.5). Theoretically, EC and inventory based-NEE measures are independent assessments of annual carbon sequestration rates with unrelated errors (Black *et al.*, 2006). Therefore, intercomparisons provide the potential for investigating the causes of inter-annual and site specific variations in NEE (Curtis *et al.*, 2002).

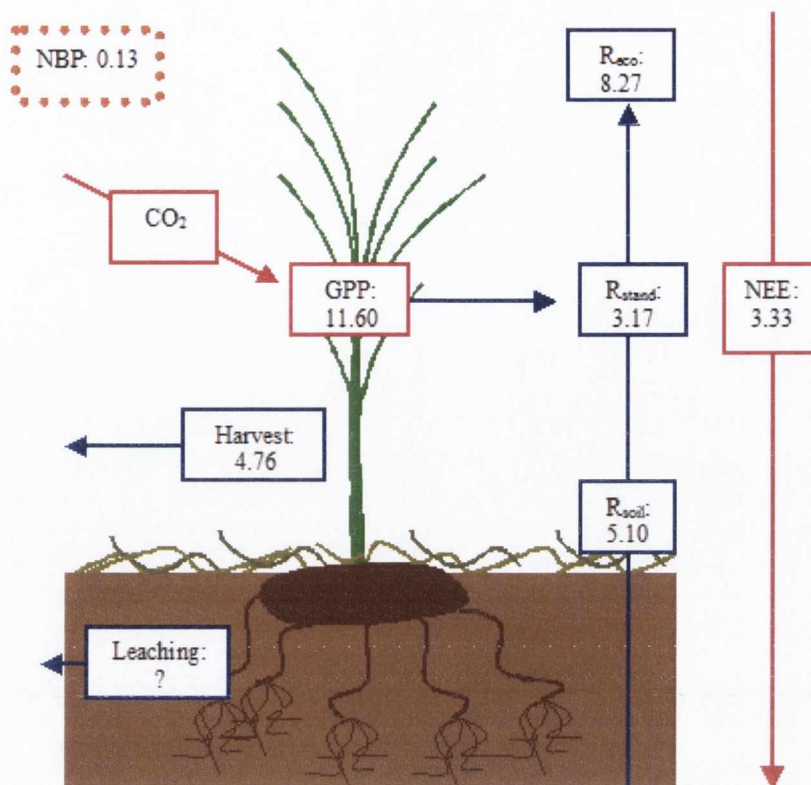


Figure 5.4: Averaged annual flux carbon cycle for a *Miscanthus x giganteus* stand, expressed in $\text{t C ha}^{-1} \text{ yr}^{-1}$, based on data from the EC study and soil chambers measurements, collected between August 2006 to August 2008 from Oak Park Research Centre, Co. Carlow.

GPP, NEE and R_{eco} data presented in the flux carbon cycle (Figure 5.4) were the average of the annual sums from Year 1 and Year 2 reported in Chapter 3. Based on the component flux analysis, approximately 27% of the C gained via gross primary production (GPP) is lost due to stand respiration, the remaining carbon is fixed into above and below-ground biomass. Stand respiration could not be divided into autotrophic and heterotrophic respiration fluxes as there was insufficient replication in leaf respiration measurements and no estimates of stem, litter, harvest-residue or root respiration fluxes. R_{stand} was defined as R_{eco} (as described in Chapter 3) less R_{soil} (calculated from chamber flux measurements collected from October 2006 to 2007, section 5.1.2). Leaching, run-off and herbivory were not measured but were assumed to be negligible. NBP value reported was an average of the NBP calculated for the two study years (Chapter 5). An average NBP of 0.13 t C ha^{-1} suggests that the *Miscanthus* stand acted as a net sink of carbon over the study period, even after the release of carbon stored in biomass is considered. This carbon sink was available for sequestration into the underlying soil and below-ground structures. Previous soil organic carbon accumulation rates of $0.86 \text{ t C ha}^{-1} \text{ yr}^{-1}$ (Matthews and Grogan, 2001) and $2\text{--}3 \text{ t C ha}^{-1} \text{ yr}^{-1}$ (Dondini *et al.*, 2009) have been reported for *Miscanthus* plantations in Ireland, depending on previous land use, crop yields and the initial SOC contents.

It is important to note that the presented carbon cycle does not include carbon fluxes associated with crop management or transport emissions. Acaroglu and Aksoy (2005) have previously reported on the CO₂ emissions arising from the cultivation of *Miscanthus* in Turkey, accounting for emissions produced from fertiliser and machinery manufacturing, transport fuels and the construction and maintenance of energy plants. The potential viability of growing *Miscanthus* in Ireland, as a means of mitigating CO₂ emissions, will depend strongly on whether such emissions are included in the final crop carbon balance

Figure 5.5 shows the quantity of carbon stored in the different above and below-ground pools in a *Miscanthus* stand. The carbon content stored by biomass into foliage and stem was estimated based on data from the 2007/2008 biomass sampling campaign detailed in section 2.2.1. Input of harvest residue was obtained from data in Chapter 2 and relates to the 2007/2008 growing seasons. Leaf litter input was based on the average annual litter fall data recorded in litter traps from the 2006/2007 and 2007/2008 seasons. Below-ground biomass values represented the mean carbon content of the rhizomes and roots over the entire study period. Based on findings from a near-by *Miscanthus* plantation, approximately 2-3 t C ha⁻¹ is likely to accumulate in the underlying soil annually (Doncini *et al.*, 2009).

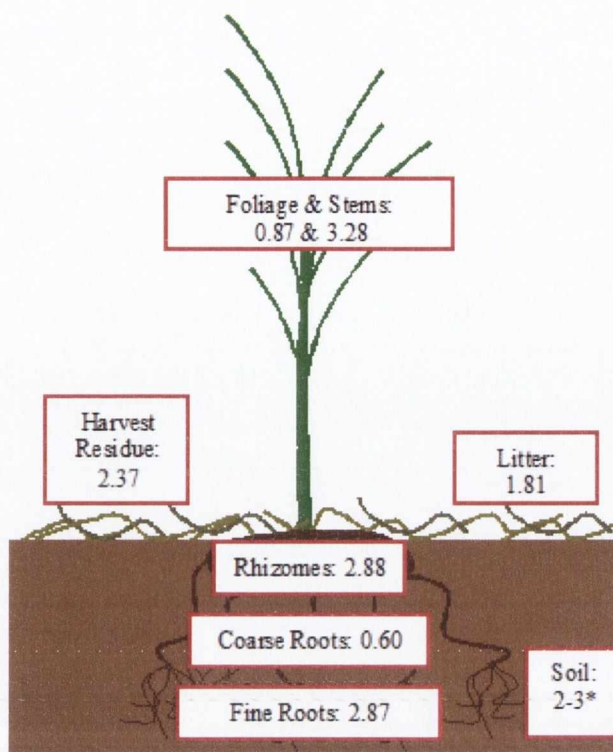


Figure 5.5: Estimated carbon content in above and below ground pools for a *Miscanthus x giganteus* stand, expressed in t C ha⁻¹ yr⁻¹, based on inventory and biometric measurements collected between August 2006 to August 2008 from Oak Park Research Centre, Co. Carlow. * based on findings by Dondini *et al.* (2009).

5.2: Study Findings:

- The *Miscanthus* stand was a NBP source of carbon in Year 1 and a net sink in Year 2 (-0.47 t C ha⁻¹ and 0.73 t C ha⁻¹ respectively). Lower R_{eco} fluxes in Year 2 appeared to be the dominant control on interannual variation in the net carbon sink-source status of crop.
- The annual mean soil respiration rate for the *Miscanthus* stand was calculated as 6.59 g CO₂ m⁻² day⁻¹. Maximum soil respiration rates were recorded in the summer months (10.55 g CO₂ m⁻² day⁻¹) and minimum values were seen in the winter months (0.52 g CO₂ m⁻² day⁻¹). Soil respiration and soil temperature had an intermediate strength correlation (r=0.451; P=0.002); while soil respiration and soil moisture were not significantly correlated (r, 0.243; P value, 0.265). Fluxes from the soil in the *Miscanthus* stand, representing 60.25% of the TER fluxes.
- Typical midday CO₂ assimilation rates at the Oak Park site were 4 to 6 μmol CO₂ m⁻² s⁻¹ (June to October) with highest CO₂ assimilation rates in both sunlit and shaded leaves recorded in July. The *Miscanthus* leaves exhibited relatively low Φ values (0.002 to 0.049) and light saturation was not achieved up to a PPFD of 1991 μmol m⁻² s⁻¹.

- During this study maximum above ground biomass was recorded in November 2006 (23.60 t DM ha⁻¹) and September 2007 (20.95 t DM ha⁻¹). 96.62% of the below ground biomass was located in the top 30 cm of the soil; an average of 6.11 t DM ha⁻¹ of rhizome material and 7.36 t DM ha⁻¹ of root material was calculated.
- Litter fall rates were 9.12 g DM m⁻² day⁻¹ and 3.18 g DM m⁻² day⁻¹ over the winters of 2006/2007 and 2007/2008. An average 4.65 and 3.08 t DM ha⁻¹ of leaf litter fell in both years. A decay constant of 0.58 was derived for the *Miscanthus* stand, indicating that 70% of the litter would decompose over 20 months providing a large amount of organic matter into the ecosystem.
- Weed species numbers decreased with canopy closure.

5.3: Further Studies:

A possible future study would involve comparing the eddy covariance fluxes measured over the *Miscanthus* stand in Oak Park with those currently being recorded in the Carbo-BioCrop study in the UK, comparing the effect of crop age, climatic and edaphic conditions on NEE fluxes. Long-term studies over *Miscanthus*, and energy crops in general, are required to evaluate the effects of the crop life cycle on carbon stocks. In general, further analysis is required to indicate the most desirable site locations and efficient management practices to encourage carbon sequestration.

5.4: Concluding Remarks:

This project set out to quantify the fluxes of CO₂ between the atmosphere and a *Miscanthus* stand at the ecosystem, leaf and soil levels over two calendar years. A secondary aim was to measure the productivity of the *Miscanthus* crop. Finally, the carbon sink or source strength of the *Miscanthus* ecosystem was to be determined and the potential of growing the bioenergy crop on Irish arable land, as a means of contributing towards our national CO₂ abatement targets, was to be determined. The work described in this study has successfully addressed these key aims. The micrometeorological measurements have highlighted the potential of *Miscanthus* as significant carbon sinks at the net ecosystem and net biomass production levels. Research on the carbon dynamics of *Miscanthus* from establishment to removal would permit the completion of the carbon cycle for the crop and the sink-source strength of the total life cycle could be established. This is an important factor when considering the need for sustainable, long term, carbon efficient fuels. The provision of longer-term EC data would facilitate the development of comprehensive carbon balance model that could be used to stimulate the effect of stand age, management

practices, land-use change and climate change scenarios on carbon fluxes. In conclusion, based on the findings in this study, the use of *Miscanthus* as a viable option for carbon mitigation in Ireland is strongly advocated; however, longer term studies are required to determine the sustainability of the near- and better than-carbon neutral status of the crop.

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Appendix 1: Abundance of understory species present in a *Miscanthus* stand located in Oak Park Research Centre, Co. Carlow, in August 2006. Cover abundance indices follow Braun-Blanquet (1932).

T	Species Present	Scale	T	Species Present	Scale
1	<i>Miscanthus giganteus</i>	5	9	<i>M. giganteus</i>	5
	<i>Rubus fruticosus</i> L.	2		<i>R. fruticosus</i> L.	R
	<i>Poa annua</i> L.	2		<i>G. aparine</i> L.	2
	<i>Galium aparine</i> L.	R		<i>C. arvense</i>	R
2	<i>M. giganteus</i>	4	10	<i>M. giganteus</i>	5
	<i>P. annua</i> L.	5		<i>R. fruticosus</i> L.	2
	<i>Festuca rubra</i>	3		<i>G. aparine</i> L.	R
	<i>Heracleum sphondylium</i> L.	2		<i>P. annua</i> L.	3
3	<i>M. giganteus</i>	4	11	<i>M. giganteus</i>	4
	<i>P. annua</i> L.	5		<i>R. fruticosus</i> L.	3
	<i>G. aparine</i> L.	2		<i>G. aparine</i> L.	2
	<i>Dactylis glomerata</i>	3		<i>P. annua</i> L.	2
	<i>F. rubra</i>	2	12	<i>M. giganteus</i>	4
4	<i>M. giganteus</i>	5		<i>R. fruticosus</i> L.	2
	<i>P. annua</i> L.	5		<i>Hypochoeris radicata</i>	R
	<i>F. rubra</i>	5		<i>P. annua</i> L.	5
5	<i>M. giganteus</i>	5	13	<i>M. giganteus</i>	5
	<i>Urtica dioica</i>	1		<i>P. annua</i> L.	3
	<i>Cirsium arvense</i>	R		<i>G. aparine</i> L.	1
	<i>G. aparine</i> L.	R		<i>Taraxacum officinale</i> Weber	+
6	<i>M. giganteus</i>	5		<i>H. radicata</i>	R
	<i>U. dioica</i>	2		<i>C. arvense</i>	+
	<i>Hedera helix</i> L.	R	14	<i>M. giganteus</i>	5
	<i>G. aparine</i> L.	R		<i>P. annua</i> L.	2
	<i>R. fruticosus</i> L.	R		<i>U. dioica</i>	2
7	<i>M. giganteus</i>	5		<i>G. aparine</i> L.	R
	<i>G. aparine</i> L.	2	15	<i>M. giganteus</i>	5
	<i>R. fruticosus</i> L.	R		<i>P. annua</i> L.	1
8	<i>M. giganteus</i>	5		<i>U. dioica</i>	R
	<i>R. fruticosus</i> L.	2		<i>G. aparine</i> L.	R
	<i>G. aparine</i> L.	2	16	<i>M. giganteus</i>	5
	<i>U. dioica</i>	R		<i>G. aparine</i> L.	R
				<i>Ranunculus repens</i>	R
				<i>Trifolium repens</i>	R

Appendix 1 (cont): Abundance of understory species present in a *Miscanthus* stand located in Oak Park Research Centre, Co. Carlow, in August 2006. Cover abundance indices follow Braun-Blanquet (1932).

T	Species Present	Scale	T	Species Present	Scale
17	<i>M. giganteus</i> <i>P. annua</i> L. <i>Sphagnum</i> sp. <i>Taraxacum officinale</i> Weber <i>Heracleum sphondylium</i> L.	4 5 3 + R	26	<i>M. giganteus</i> <i>Galium aparine</i> L. <i>P. annua</i> L. <i>Rubus fruticosus</i> L. <i>Ranunculus repens</i>	5 2 5 1 +
18	<i>M. giganteus</i> <i>P. annua</i> L. <i>Sphagnum</i> sp.	5 5 R	27	<i>M. giganteus</i> <i>P. annua</i> L. <i>Rubus fruticosus</i> L. <i>Urtica dioica</i> <i>Hypochoeris radicata</i>	5 4 1 3 R
19	<i>M. giganteus</i> <i>P. annua</i> L. <i>Sphagnum</i> sp. <i>Rubus fruticosus</i> L.	5 1 2 2	28	<i>M. giganteus</i> <i>P. annua</i> L. <i>Rubus fruticosus</i> L. <i>Galium aparine</i> L. <i>Epilobium angustifolium</i> L.	5 3 2 2 3
20	<i>M. giganteus</i> <i>Rubus fruticosus</i> L. <i>P. annua</i> L. <i>Galium aparine</i> L.	4 2 5 1	29	<i>Miscanthus sinensis</i> <i>P. annua</i> L. <i>Galium aparine</i> L. <i>Cirsium arvense</i> <i>Urtica dioica</i> <i>Taraxacum officinale</i> Weber	5 5 R 2 1 R
21	<i>M. giganteus</i> <i>P. annua</i> L. <i>Galium aparine</i> L.	5 2 5	30	<i>M. giganteus</i> <i>Rubus fruticosus</i> L. <i>Sphagnum</i> sp. <i>P. annua</i> L. <i>Trifolium repens</i>	5 4 2 3 2
22	<i>M. giganteus</i> <i>P. annua</i> L. <i>Galium aparine</i> L. <i>Rubus fruticosus</i> L. <i>Dactylis glomerata</i>	5 3 4 2 3	31	<i>M. giganteus</i> <i>Dactylis glomerata</i> <i>Rubus fruticosus</i> L.	4 4 2
23	<i>M. giganteus</i> <i>P. annua</i> L. <i>Galium aparine</i> L. <i>Rubus fruticosus</i> L. <i>Cirsium arvense</i>	5 3 3 4 +	32	<i>M. giganteus</i> <i>P. annua</i> L. <i>Rubus fruticosus</i> L. <i>Sphagnum</i> sp. <i>Cirsium arvense</i>	5 3 2 2 1
24	<i>M. giganteus</i> <i>Cirsium arvense</i> <i>P. annua</i> L. <i>Galium aparine</i> L.	5 + 3 R	33	<i>M. giganteus</i> <i>P. annua</i> L. <i>Rubus fruticosus</i> L. <i>Taraxacum officinale</i> Weber <i>Cirsium arvense</i>	5 3 3 2 +
25	<i>M. giganteus</i> <i>Galium aparine</i> L. <i>P. annua</i> L. <i>Rubus fruticosus</i> L.	5 3 4 2			

Appendix 2: Abundance of understory species present in a *Miscanthus* stand located in Oak Park Research Centre, Co. Carlow, in March 2007. Cover abundance indices follow Braun-Blanquet (1932).

T	Species Present	Scale	T	Species Present	Scale
1	<i>Poa annua</i> L. <i>Festuca ovina</i> agg <i>Dactylis glomerata</i> <i>Miscanthus giganteus</i>	5 3 1 +	9	<i>G. aparine</i> L. <i>V. persica</i> <i>P. annua</i> L. <i>L. serriola</i> L.	3 1 1 R
2	<i>M. giganteus</i> <i>Vinca major</i> <i>Lamium album</i> <i>Agrostis stolonifera</i> <i>Festuca rubra</i>	5 R R + +	10	<i>A. stolonifera</i> <i>M. giganteus</i> <i>G. aparine</i> L. <i>L. serriola</i> L. <i>C. arvense</i>	5 3 3 1 +
3	<i>M. giganteus</i> <i>Cirsium arvense</i> <i>Urtica dioica</i> <i>P. annua</i> L.	5 3 1 1	11	<i>M. giganteus</i> <i>U. dioica</i> <i>C. arvense</i> <i>A. stolonifera</i> <i>V. persica</i>	4 2 1 1 R
4	<i>M. giganteus</i> <i>Glyceria maxima</i> <i>Veronica persica</i> <i>Rubus fruticosus</i> L. <i>C. arvense</i> <i>Galium aparine</i> L. <i>U. dioica</i>	4 4 3 1 R + +	12	<i>E. angustifolium</i> L. <i>P. annua</i> L. <i>M. giganteus</i> <i>R. fruticosus</i> L. <i>A. stolonifera</i> <i>F. ovina</i> agg. <i>C. arvense</i>	5 4 2 2 1 1 1
5	<i>M. giganteus</i> <i>G. aparine</i> L. <i>V. persica</i> <i>R. fruticosus</i> L. <i>Rosa canina</i> L. <i>Taraxacum officinale</i> Weber <i>Epilobium angustifolium</i> L. <i>Aegopodium podagraria</i> L.	4 2 2 1 1 R R R	13	<i>M. giganteus</i> <i>A. stolonifera</i> <i>C. arvense</i> <i>F. rubra</i> <i>V. persica</i> <i>Papaver rhoeas</i> L. <i>E. angustifolium</i> L. <i>Sonchus arvensis</i> L. <i>G. aparine</i> L. <i>Stachys arvensis</i> L.	5 5 2 R R + + + + +
6	<i>M. giganteus</i> <i>G. aparine</i> L. <i>R. fruticosus</i> L. <i>A. stolonifera</i> <i>Geum urbanum</i> <i>F. rubra</i> <i>V. persica</i> <i>Lactuca serriola</i> L.	5 3 2 2 1 R R +	14	<i>R. fruticosus</i> L. <i>P. annua</i> L. <i>M. giganteus</i> <i>C. arvense</i> <i>V. Persica</i>	4 4 3 1 1
7	<i>M. giganteus</i> <i>R. fruticosus</i> L. <i>C. arvense</i> <i>F. rubra</i>	5 4 4 1	15	<i>M. giganteus</i> <i>C. arvense</i> <i>E. angustifolium</i> L. <i>S. arvensis</i> L. <i>L. serriola</i> L. <i>V. persica</i> <i>Lolium perenne</i>	3 2 1 + + + +
8	<i>M. giganteus</i> <i>C. arvense</i> <i>A. stolonifera</i> <i>P. annua</i> L. <i>G. aparine</i> L.	5 5 3 1 1	16	<i>M. giganteus</i> <i>Equisteum pratense</i> <i>C. arvense</i> <i>E. angustifolium</i> L. <i>P. annua</i> L.	5 1 1 1 1
9	<i>G. urbanum</i> <i>R. fruticosus</i> L. <i>M. giganteus</i>	5 4 3			

Appendix 2 (cont): Abundance of understory species present in a *Miscanthus* stand located in Oak Park Research Centre, Co. Carlow, in March 2007. Cover abundance indices follow Braun-Blanquet (1932)

T	Species Present	Scale	T	Species Present	Scale
17	<i>M. giganteus</i>	5	26	<i>M. giganteus</i>	5
	<i>A. stolonifera</i>	3		<i>C. arvense</i>	4
	<i>L. serriola</i> L.	R		<i>G. aparine</i> L.	2
18	<i>M. giganteus</i>	5		<i>R. fruticosus</i> L.	2
	<i>L. perenne</i>	3		<i>G. urbanum</i>	1
	<i>Heracleum sphondylium</i> L.	1		<i>T. officinale</i> Weber	R
	<i>C. arvense</i>	+	27	<i>L. perenne</i>	5
19	<i>M. giganteus</i>	4		<i>M. giganteus</i>	3
	<i>A. stolonifera</i>	1		<i>C. arvense</i>	2
	<i>L. perenne</i>	1		<i>R. fruticosus</i> L.	2
	<i>R. fruticosus</i> L.	1		<i>G. aparine</i> L.	1
	<i>G. urbanum</i>	1	28	<i>M. giganteus</i>	5
	<i>Sonchus oleraceus</i> L.	R		<i>U. diocia</i>	2
	<i>S. arvensis</i> L.	R		<i>G. aparine</i> L.	1
	<i>V. perisca</i>	R		<i>S. oleraceus</i> L.	1
	<i>Bellis perennis</i> L.	R		<i>C. arvense</i>	+
20	<i>M. giganteus</i>	5		<i>V. perica</i>	+
	<i>H. sphondylium</i> L.	4		<i>E. angustifolium</i> L.	+
	<i>P. annua</i> L.	1		<i>Geranium robertianum</i> L.	+
	<i>V. perisca</i>	R	29	<i>M. giganteus</i>	3
	<i>R. fruticosus</i> L.	+		<i>F. rubra</i>	3
21	<i>M. giganteus</i>	2		<i>P. annua</i> L.	2
	<i>U. diocia</i>	2		<i>T. officinale</i> Weber	1
	<i>S. arvensis</i> L.	1	30	<i>M. giganteus</i>	4
22	<i>M. giganteus</i>	5		<i>R. fruticosus</i> L.	2
	<i>C. arvense</i>	3		<i>T. officinale</i> Weber	2
	<i>U. diocia</i>	3		<i>V. perica</i>	1
	<i>G. aparine</i> L.	3		<i>L. perenne</i>	1
	<i>R. fruticosus</i> L.	1		<i>G. aparine</i> L.	1
	<i>S. arvensis</i> L.	1	31	<i>M. giganteus</i>	3
23	<i>M. giganteus</i>	5		<i>V. perica</i>	3
	<i>G. aparine</i> L.	4		<i>C. arvense</i>	2
	<i>C. arvense</i>	4		<i>S. oleraceus</i> L.	1
	<i>R. fruticosus</i> L.	3		<i>G. aparine</i> L.	1
	<i>G. urbanum</i>	2	32	<i>M. giganteus</i>	5
	<i>U. diocia</i>	1		<i>A. stolonifera</i>	5
	<i>Hedera helix</i> L. (Ivy)	R		<i>C. arvense</i>	3
	<i>E. angustifolium</i> L.	+		<i>G. aparine</i> L.	3
24	<i>M. giganteus</i>	5		<i>L. perenne</i>	2
	<i>G. aparine</i> L.	5		<i>U. diocia</i>	+
	<i>G. urbanum</i>	2	33	<i>M. giganteus</i>	4
	<i>C. arvense</i>	2		<i>C. arvense</i>	3
	<i>V. perica</i>	2		<i>A. stolonifera</i>	3
	<i>E. angustifolium</i> L.	1		<i>D. glomerata</i>	2
	<i>R. fruticosus</i> L.	1			
25	<i>M. giganteus</i>	5			
	<i>C. arvense</i>	3			
	<i>R. fruticosus</i> L.	2			
	<i>G. urbanum</i>	2			
	<i>H. sphondylium</i> L.	1			
	<i>U. diocia</i>	+			
	<i>G. aparine</i> L.	+			

Appendix 3: Abundance of understory species present in a *Miscanthus* stand located in Oak Park Research Centre, Co. Carlow, in May 2007. Cover abundance indices follow Braun-Blanquet (1932).

Q	Species Present	Scale	Q	Species Present	Scale
1	Litter (mainly stems)	5	6	Litter (mainly stems)	5
	<i>Miscanthus giganteus</i>	3		<i>Miscanthus giganteus</i>	3
	<i>Agrostis stolonifera</i>	3		<i>Rubus fruticosus</i> L.	2
	<i>Galium aparine</i> L.	+		<i>Galium aparine</i> L.	2
	<i>Veronica persica</i>	2		<i>Cirsium arvense</i>	2
	<i>Hedera helix</i>	+		Sonchus oleraceus	2
	<i>Taraxacum officinale</i> Weber	+	7	Litter (mainly stems)	5
2	Litter (mainly stems)	5		<i>Miscanthus giganteus</i>	3
	<i>Miscanthus giganteus</i>	3		<i>Galium aparine</i> L.	3
	<i>Galium aparine</i> L.	2		<i>Rubus fruticosus</i> L.	2
	<i>Rubus fruticosus</i> L.	2		<i>Urtica dioica</i>	2
	<i>Cirsium arvense</i>	+		<i>Agrostis stolonifera</i>	2
3	Litter (mainly stems)	5	8	Litter (mainly stems)	5
	<i>Miscanthus giganteus</i>	3		<i>Miscanthus giganteus</i>	4
	<i>Cirsium arvense</i>	3		<i>Veronica persica</i>	3
	<i>Urtica dioica</i>	2		<i>Cirsium arvense</i>	1
	<i>Rubus fruticosus</i> L.	+		<i>Galium aparine</i> L.	1
	<i>Poa annua</i> L.	2		Sonchus oleraceus	1
4	Litter (mainly stems)	5		<i>Rubus fruticosus</i> L.	+
	<i>Miscanthus giganteus</i>	4	9	Litter (mainly stems)	5
	<i>Dactylis glomerata</i>	4		<i>Miscanthus giganteus</i>	5
	<i>Galium aparine</i> L.	+		<i>Rubus fruticosus</i> L.	2
	<i>Lactuca serriola</i> L.	+		<i>Cirsium arvense</i>	2
				<i>Galium aparine</i> L.	2
5	Litter (mainly stems)	4		<i>Agrostis stolonifera</i>	1
	<i>Miscanthus giganteus</i>	4		<i>Veronica persica</i>	2
	<i>Cirsium arvense</i>	4	10	Litter (mainly stems)	5
	<i>Galium aparine</i> L.	2		<i>Miscanthus giganteus</i>	4
	<i>Epilobium angustifolium</i> L.	2		<i>Urtica dioica</i>	3
	<i>Rubus fruticosus</i> L.	2		<i>Cirsium arvense</i>	2
				<i>Galium aparine</i> L.	2
				<i>Agrostis stolonifera</i>	2

Appendix 4 : Abundance of understory species present in a *Miscanthus* stand located in Oak Park Research Centre, Co. Carlow, in June 2007. Cover abundance indices follow Braun-Blanquet (1932).

Q	Species Present	Scale	Q	Species Present	Scale
1	Litter (mainly stems)	5	6	Litter (mainly stems)	5
	<i>Miscanthus giganteus</i>	4		<i>Miscanthus giganteus</i>	3
	<i>Agrostis stolonifera</i>	3		<i>Rubus fruticosus</i> L.	2
	<i>Galium aparine</i> L.	+		<i>Galium aparine</i> L.	+
	<i>Veronica persica</i>	2		<i>Cirsium arvense</i>	2
	<i>Hedera helix</i>	+		<i>Agrostis stolonifera</i>	2
	Sonchus oleraceus	+		Sonchus oleraceus	2
	<i>Rubus fruticosus</i> L.	+		Litter (mainly stems)	5
2	Litter (mainly stems)	5	7	<i>Miscanthus giganteus</i>	3
	<i>Miscanthus giganteus</i>	4		<i>Galium aparine</i> L.	3
	<i>Galium aparine</i> L.	3		<i>Rubus fruticosus</i> L.	2
	<i>Rubus fruticosus</i> L.	2		<i>Agrostis stolonifera</i>	2
	<i>Cirsium arvense</i>	2		Litter (mainly stems)	5
	<i>Veronica persica</i>	+	8	<i>Miscanthus giganteus</i>	4
3	Litter (mainly stems)	5		<i>Veronica persica</i>	2
	<i>Miscanthus giganteus</i>	4		<i>Cirsium arvense</i>	2
	<i>Cirsium arvense</i>	3		<i>Galium aparine</i> L.	2
	<i>Urtica dioica</i>	R		<i>Agrostis stolonifera</i>	2
	<i>Rubus fruticosus</i> L.	+		Litter (mainly stems)	5
	<i>Poa annua</i> L.	2	9	<i>Miscanthus giganteus</i>	5
	<i>Sonchus oleraceus</i>	+		<i>Rubus fruticosus</i> L.	2
4	Litter (mainly stems)	4		<i>Cirsium arvense</i>	2
	<i>Miscanthus giganteus</i>	4		<i>Agrostis stolonifera</i>	2
	<i>Dactylis glomerata</i>	4		<i>Veronica persica</i>	2
	<i>Galium aparine</i> L.	2		Litter (mainly stems)	5
5	Litter (mainly stems)	5	10	<i>Miscanthus giganteus</i>	4
	<i>Miscanthus giganteus</i>	4		<i>Urtica dioica</i>	1
	<i>Cirsium arvense</i>	2		<i>Cirsium arvense</i>	2
	<i>Galium aparine</i> L.	2		<i>Galium aparine</i> L.	2
	<i>Epilobium angustifolium</i> L.	+		<i>Agrostis stolonifera</i>	3
	<i>Rubus fruticosus</i> L.	2		<i>Sonchus oleraceus</i>	+

Appendix 5 : Abundance of understory species present in a *Miscanthus* stand located in Oak Park Research Centre, Co. Carlow, in July 2007. Cover abundance indices follow Braun-Blanquet (1932).

Q	Species Present	Scale	Q	Species Present	Scale
1	Litter (mainly stems)	5	6	Litter (mainly stems)	5
	<i>Miscanthus giganteus</i>	5		<i>Miscanthus giganteus</i>	5
	<i>Agrostis stolonifera</i>	3		<i>Rubus fruticosus</i> L.	+
	<i>Poa annua</i> L.	4		<i>Cirsium arvense</i>	+
2	Litter (mainly stems)	5	7	<i>Agrostis stolonifera</i>	2
	<i>Miscanthus giganteus</i>	5		Litter (mainly stems)	4
	<i>Veronica persica</i>	+		<i>Miscanthus giganteus</i>	4
3	Litter (mainly stems)	5		<i>Galium aparine</i> L.	2
	<i>Miscanthus giganteus</i>	5		<i>Agrostis stolonifera</i>	5
	<i>Cirsium arvense</i>	2	8	Litter (mainly stems)	5
	<i>Poa annua</i> L.	2		<i>Miscanthus giganteus</i>	5
4	Litter (mainly stems)	5		<i>Cirsium arvense</i>	2
	<i>Miscanthus giganteus</i>	5		<i>Geranium robertianum</i>	2
	<i>Dactylis glomerata</i>	4	9	Litter (mainly stems)	5
	<i>Galium aparine</i> L.	2		<i>Miscanthus giganteus</i>	5
	<i>Cirsium arvense</i>	1		<i>Cirsium arvense</i>	+
	<i>Veronica persica</i>	2		<i>Agrostis stolonifera</i>	2
5	Litter (mainly stems)	5	10	Litter (mainly stems)	5
	<i>Miscanthus giganteus</i>	5		<i>Miscanthus giganteus</i>	5
	<i>Cirsium arvense</i>	2		<i>Cirsium arvense</i>	2
				<i>Rubus fruticosus</i> L.	3

Appendix 6 : Abundance of understory species present in a *Miscanthus* stand located in Oak Park Research Centre, Co. Carlow, in September 2007. Cover abundance indices follow Braun-Blanquet (1932).

Q	Species Present	Scale	Q	Species Present	Scale
1	Litter (mainly stems)	5	6	Litter (mainly stems)	5
	<i>Miscanthus giganteus</i>	4		<i>Miscanthus giganteus</i>	5
	<i>Agrostis stolonifera</i>	2		<i>Cirsium arvense</i>	+
	<i>Poa annua</i> L.	4		<i>Rubus fruticosus</i> L.	2
2	Litter (mainly stems)	5	7	Litter (mainly stems)	5
	<i>Miscanthus giganteus</i>	5		<i>Miscanthus giganteus</i>	5
	<i>Rubus fruticosus</i> L.	+		<i>Agrostis stolonifera</i>	2
3	Litter (mainly stems)	5	8	Litter (mainly stems)	5
	<i>Miscanthus giganteus</i>	5		<i>Miscanthus giganteus</i>	5
	<i>Cirsium arvense</i>	1	9	Litter (mainly stems)	5
	<i>Poa annua</i> L.	2		<i>Miscanthus giganteus</i>	5
4	Litter (mainly stems)	5	10	<i>Agrostis stolonifera</i>	3
	<i>Miscanthus giganteus</i>	5		Litter (mainly stems)	5
	<i>Cirsium arvense</i>	+		<i>Miscanthus giganteus</i>	5
	<i>Veronica persica</i>	+		<i>Agrostis stolonifera</i>	3
5	Litter (mainly stems)	5		<i>Rubus fruticosus</i> L.	+
	<i>Miscanthus giganteus</i>	5			
	<i>Cirsium arvense</i>	2			

Appendix 7 : Abundance of understory species present in a *Miscanthus* stand located in Oak Park Research Centre, Co. Carlow, in December 2007. Cover abundance indices follow Braun-Blanquet (1932).

Q	Species Present	Scale	Q	Species Present	Scale
1	Litter	5	6	Litter	5
	<i>Miscanthus giganteus</i>	3		<i>Miscanthus giganteus</i>	5
	<i>Poa annua</i> L.	4	7	Litter	5
2	Litter	5		<i>Miscanthus giganteus</i>	5
	<i>Miscanthus giganteus</i>	5		<i>Agrostis stolonifera</i>	2
	<i>Rubus fruticosus</i> L.	+		<i>Trifolium pratense</i> .	+
3	Litter	5	8	Litter	5
	<i>Miscanthus giganteus</i>	5		<i>Miscanthus giganteus</i>	4
	<i>Poa annua</i> L.	2	9	Litter	5
4	Litter	5		<i>Miscanthus giganteus</i>	5
	<i>Miscanthus giganteus</i>	5	10	<i>Agrostis stolonifera</i>	3
	<i>Rubus fruticosus</i> L.	+		Litter	5
5	Litter	5		<i>Miscanthus giganteus</i>	5
	<i>Miscanthus giganteus</i>	5			

Appendix 8 : Abundance of understory species present in a *Miscanthus* stand located in Oak Park Research Centre, Co. Carlow, in January 2008. Cover abundance indices follow Braun-Blanquet (1932).

Q	Species Present	Scale	Q	Species Present	Scale
1	Litter	5	6	Litter	5
	<i>Miscanthus giganteus</i>	3		<i>Miscanthus giganteus</i>	5
	<i>Poa annua</i> L.	3	7	Litter	5
2	Litter	5		<i>Miscanthus giganteus</i>	5
	<i>Miscanthus giganteus</i>	4		<i>Agrostis stolonifera</i>	2
3	Litter	5	8	Litter	5
	<i>Miscanthus giganteus</i>	5		<i>Miscanthus giganteus</i>	4
	<i>Poa annua</i> L.	2	9	Litter	5
4	Litter	5		<i>Miscanthus giganteus</i>	5
	<i>Miscanthus giganteus</i>	4	10	<i>Agrostis stolonifera</i>	3
5	Litter	5		Litter	5
	<i>Miscanthus giganteus</i>	5		<i>Miscanthus giganteus</i>	5
	<i>Cirsium arvense</i>	+			

Appendix 9 : Abundance of understory species present in a *Miscanthus* stand located in Oak Park Research Centre, Co. Carlow, in March 2008. Cover abundance indices follow Braun-Blanquet (1932).

Q	Species Present	Scale	Q	Species Present	Scale
1	Litter	5	6	Litter	5
	<i>Miscanthus giganteus</i>	5		<i>Miscanthus giganteus</i>	4
	<i>Poa annua</i> L.	3		<i>Poa annua</i> L.	3
2	Litter	5	7	Litter	5
	<i>Miscanthus giganteus</i>	3		<i>Miscanthus giganteus</i>	5
	<i>Rubus fruticosus</i> L.	+		<i>Agrostis stolonifera</i>	3
3	Litter	5	8	Litter	5
	<i>Miscanthus giganteus</i>	5		<i>Miscanthus giganteus</i>	5
4	Litter	5	9	Litter	5
	<i>Miscanthus giganteus</i>	5		<i>Miscanthus giganteus</i>	5
	<i>Poa annua</i> L.	2		<i>Agrostis stolonifera</i>	3
5	Litter	5	10	Litter	5
	<i>Miscanthus giganteus</i>	4		<i>Miscanthus giganteus</i>	5

Appendix 10 : Abundance of understory species present in a *Miscanthus* stand located in Oak Park Research Centre, Co. Carlow, in May 2008. Cover abundance indices follow Braun-Blanquet (1932).

Q	Species Present	Scale	Q	Species Present	Scale
1	Litter	5	6	Litter	5
	<i>Miscanthus giganteus</i>	4		<i>Miscanthus giganteus</i>	5
	<i>Rubus fruticosus</i> L.	+	7	Litter	5
	<i>Epilobium angustifolium</i> L.	R		<i>Miscanthus giganteus</i>	5
2	Litter	5		<i>Rubus fruticosus</i> L.	2
	<i>Miscanthus giganteus</i>	4	8	Litter	5
	<i>Cirsium arvense</i>	+		<i>Miscanthus giganteus</i>	5
3	Litter	5		<i>Rubus fruticosus</i> L.	+
	<i>Miscanthus giganteus</i>	5	9	Litter	5
	<i>Cirsium arvense</i>	2		<i>Miscanthus giganteus</i>	5
4	Litter	5		<i>Agrostis stolonifera</i>	3
	<i>Miscanthus giganteus</i>	4		<i>Taraxacum officinale</i> Weber	+
5	Litter	5	10	Litter	5
	<i>Miscanthus giganteus</i>	3		<i>Miscanthus giganteus</i>	4

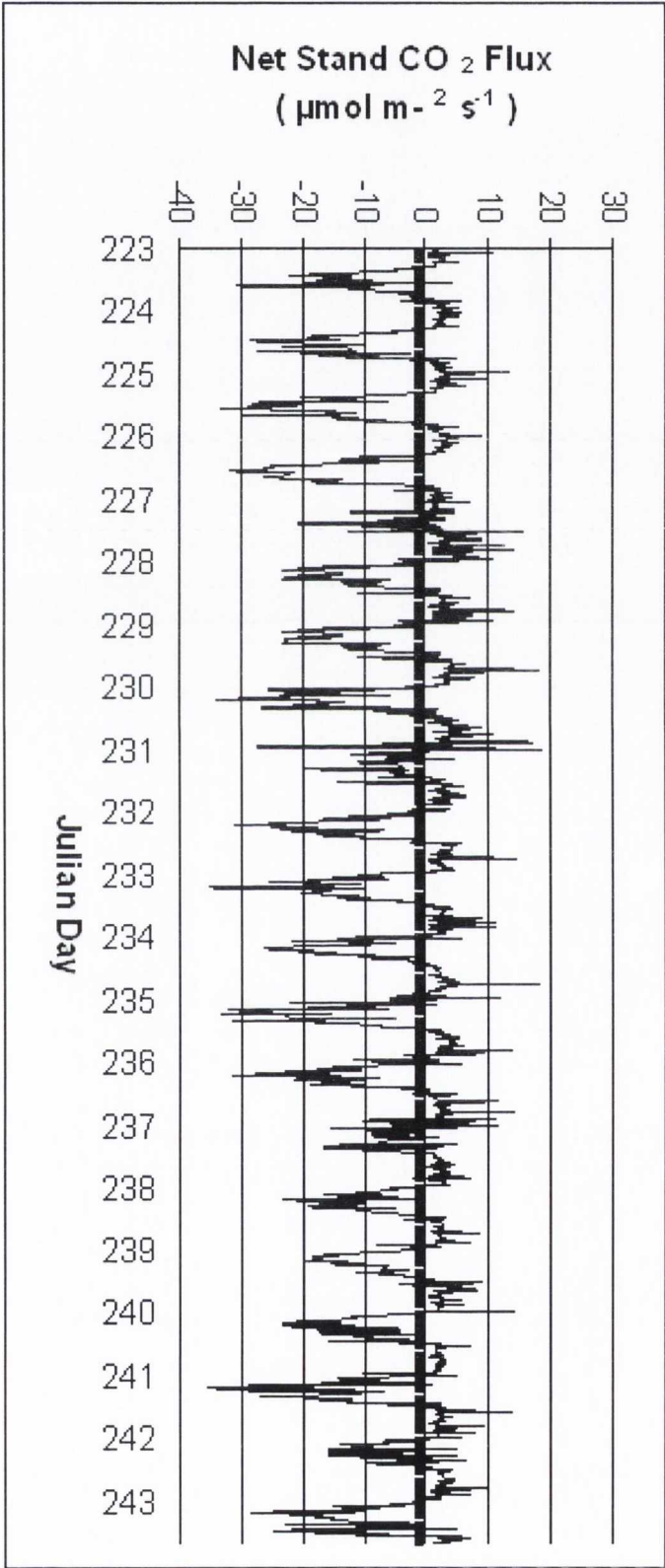
Appendix 11 : Abundance of understory species present in a *Miscanthus* stand located in Oak Park Research Centre, Co. Carlow, in June 2008. Cover abundance indices follow Braun-Blanquet (1932).

Q	Species Present	Scale	Q	Species Present	Scale
1	Litter	5	6	Litter	5
	<i>Miscanthus giganteus</i>	4		<i>Miscanthus giganteus</i>	5
	<i>Rubus fruticosus</i> L.	2	7	Litter	5
	<i>Epilobium angustifolium</i> L.	2		<i>Miscanthus giganteus</i>	5
	<i>Cirsium arvense</i>	2		<i>Rubus fruticosus</i> L.	2
2	Litter	5	8	Litter	5
	<i>Miscanthus giganteus</i>	4		<i>Miscanthus giganteus</i>	5
	<i>Cirsium arvense</i>	2		<i>Rubus fruticosus</i> L.	+
3	Litter	5		<i>Galium aparine</i> L.	+
	<i>Miscanthus giganteus</i>	5	9	Litter	5
	<i>Cirsium arvense</i>	2		<i>Miscanthus giganteus</i>	5
4	Litter	5		<i>Agrostis stolonifera</i>	2
	<i>Miscanthus giganteus</i>	4		<i>Taraxacum officinale</i> Weber	+
5	Litter	5		<i>Epilobium angustifolium</i> L.	+
	<i>Miscanthus giganteus</i>	3	10	Litter	5
				<i>Miscanthus giganteus</i>	4
				<i>Epilobium angustifolium</i> L.	+

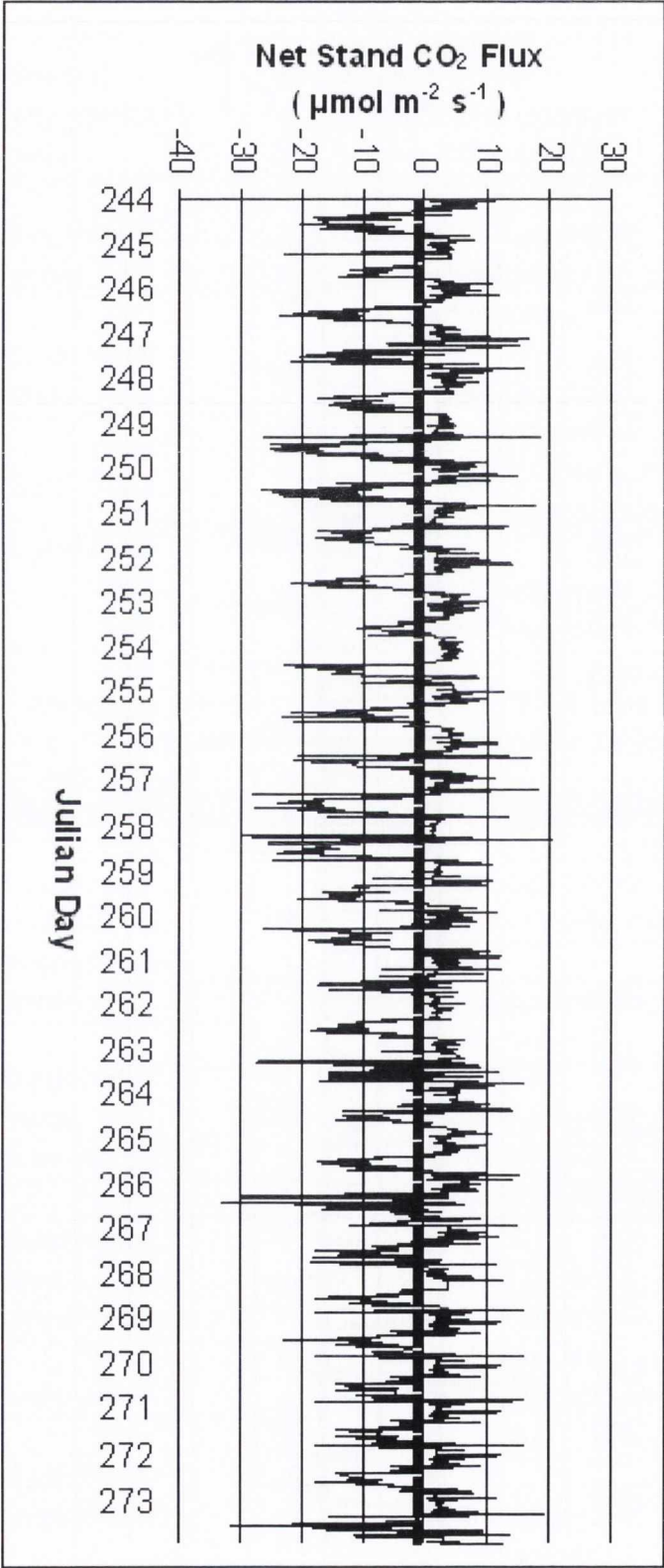
Appendix 12 : Abundance of understory species present in a *Miscanthus* stand located in Oak Park Research Centre, Co. Carlow, in July 2008. Cover abundance indices follow Braun-Blanquet (1932).

Q	Species Present	Scale	Q	Species Present	Scale
1	Litter	5	6	Litter	5
	<i>Miscanthus giganteus</i>	4		<i>Miscanthus giganteus</i>	4
	<i>Rubus fruticosus</i> L.	2		<i>Epilobium angustifolium</i> L.	2
	<i>Epilobium angustifolium</i> L.	2	7	Litter	5
	<i>Cirsium arvense</i>	+		<i>Miscanthus giganteus</i>	5
2	Litter	5	8	<i>Rubus fruticosus</i> L.	2
	<i>Miscanthus giganteus</i>	5		Litter	5
	<i>Cirsium arvense</i>	+	8	<i>Miscanthus giganteus</i>	5
	<i>Rubus fruticosus</i> L.	2		<i>Rubus fruticosus</i> L.	+
3	Litter	5	8	<i>Epilobium angustifolium</i> L.	+
	<i>Miscanthus giganteus</i>	5		Litter	5
	<i>Cirsium arvense</i>	+	9	<i>Miscanthus giganteus</i>	5
	<i>Epilobium angustifolium</i> L.	+		<i>Agrostis stolonifera</i>	3
4	Litter	5		<i>Rubus fruticosus</i> L.	2
	<i>Miscanthus giganteus</i>	4		<i>Epilobium angustifolium</i> L.	2
5	Litter	5		<i>Urtica dioica</i>	+
	<i>Miscanthus giganteus</i>	4	10	Litter	5
	<i>Epilobium angustifolium</i> L.	2		<i>Miscanthus giganteus</i>	4
				<i>Rubus fruticosus</i> L.	2

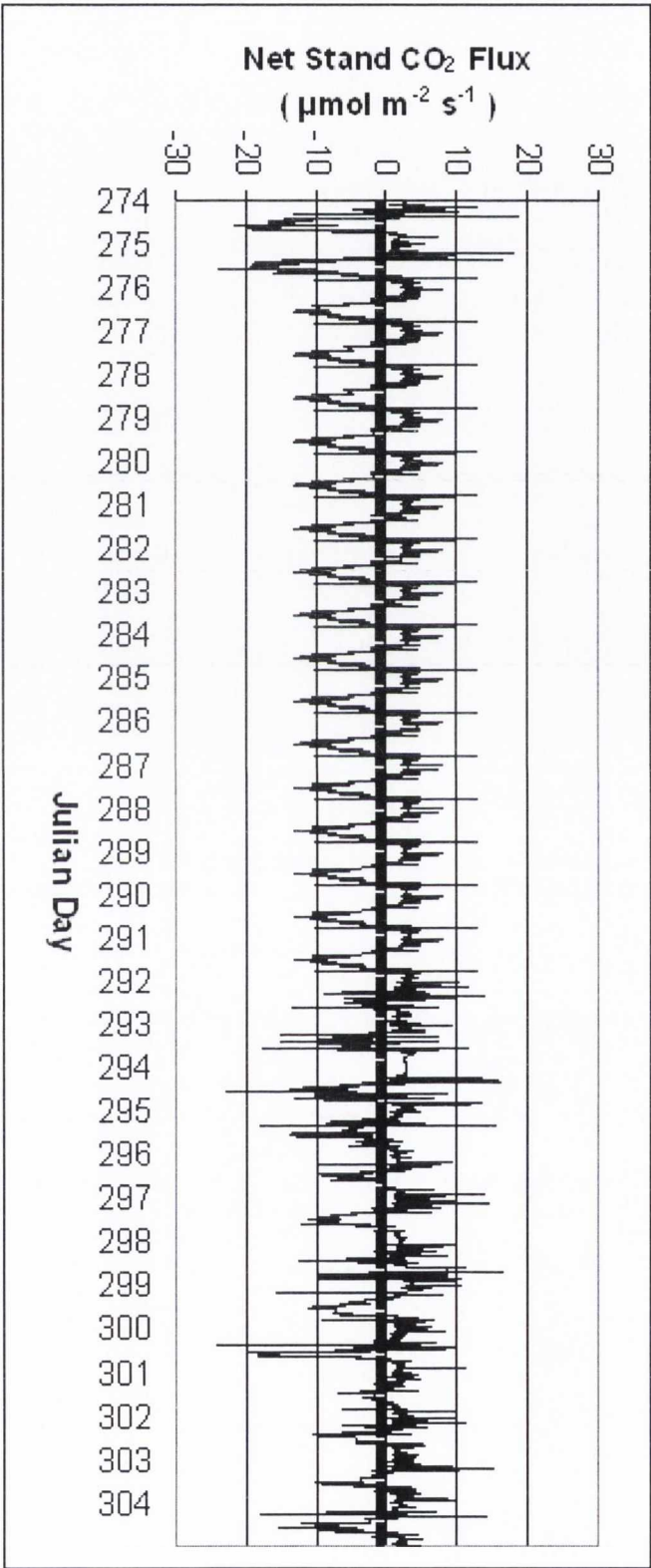
Appendix 13 : Net Stand CO₂ Flux measured above a homogenous *Miscanthus x giganteus* canopy at Oak Park Research Centre, Co. Carlow. Data collected from the 11th of August 2006 to the 31st of August 2006. Negative values indicate a net gain of CO₂ by the ecosystem; positive values indicate a net loss of CO₂ from the ecosystem.



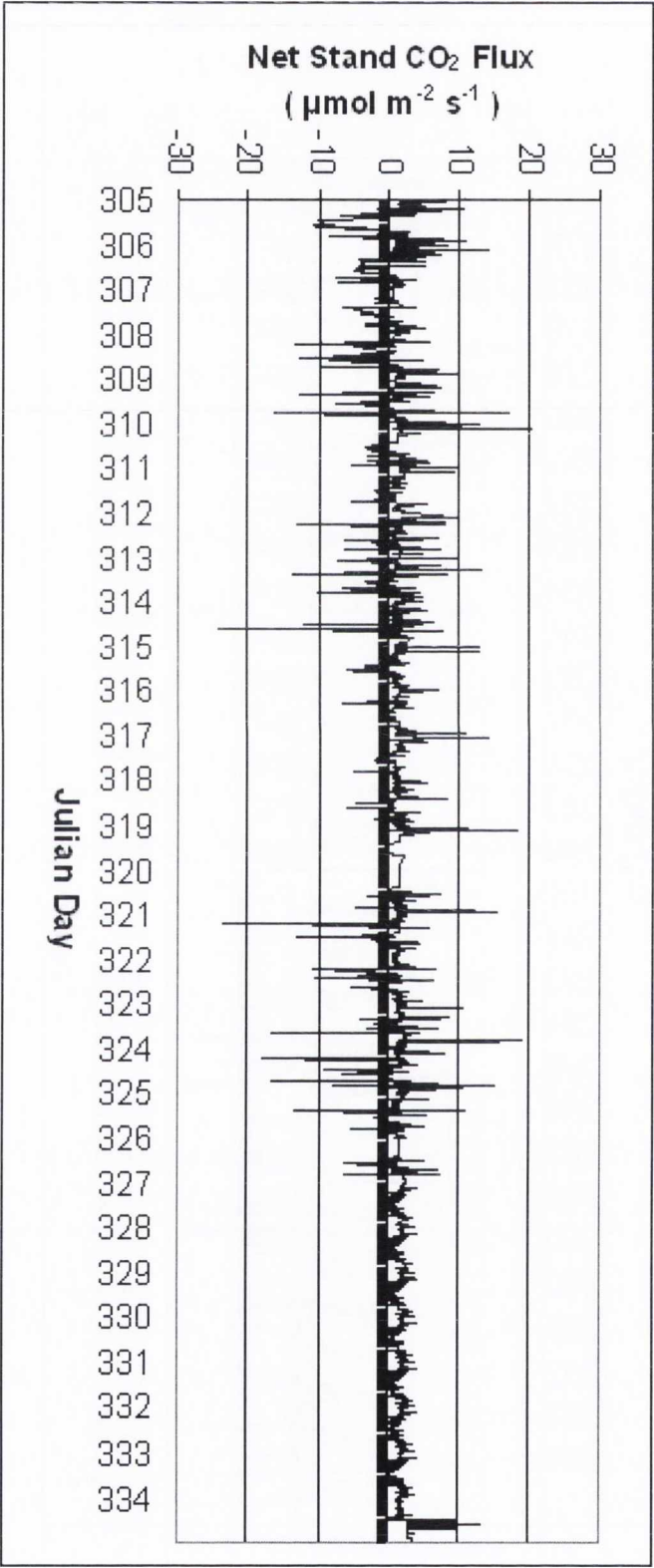
Appendix 14 : Net Stand CO₂ Flux measured above a homogenous *Miscanthus x giganteus* canopy at Oak Park Research Centre, Co. Carlow. Data collected from the 1st of September 2006 to the 30th of September 2006. Negative values indicate a net gain of CO₂ by the ecosystem; positive values indicate a net loss of CO₂ from the ecosystem.



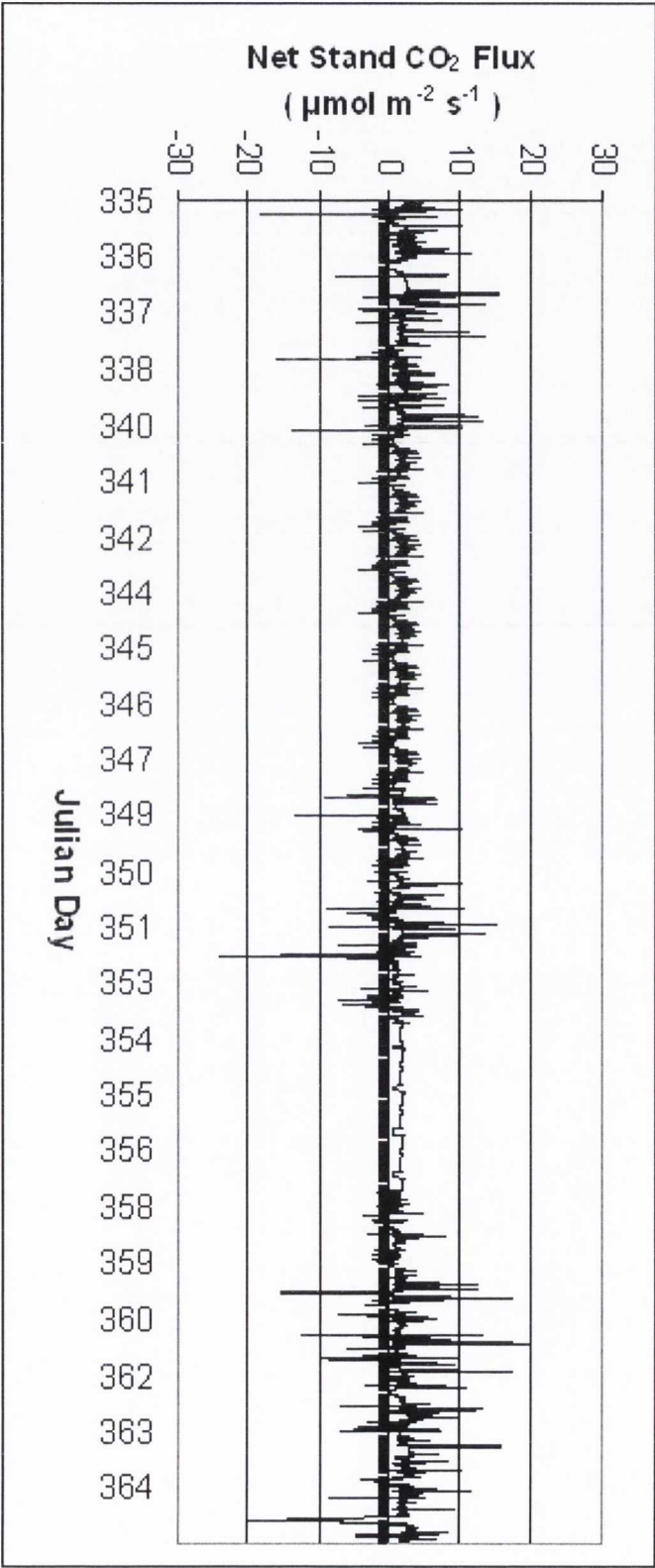
Appendix 15 : Net Stand CO₂ Flux measured above a homogenous *Miscanthus x giganteus* canopy at Oak Park Research Centre, Co. Carlow. Data collected from the 1st of October 2006 to the 31st of October 2006. Negative values indicate a net gain of CO₂ by the ecosystem; positive values indicate a net loss of CO₂ from the ecosystem.



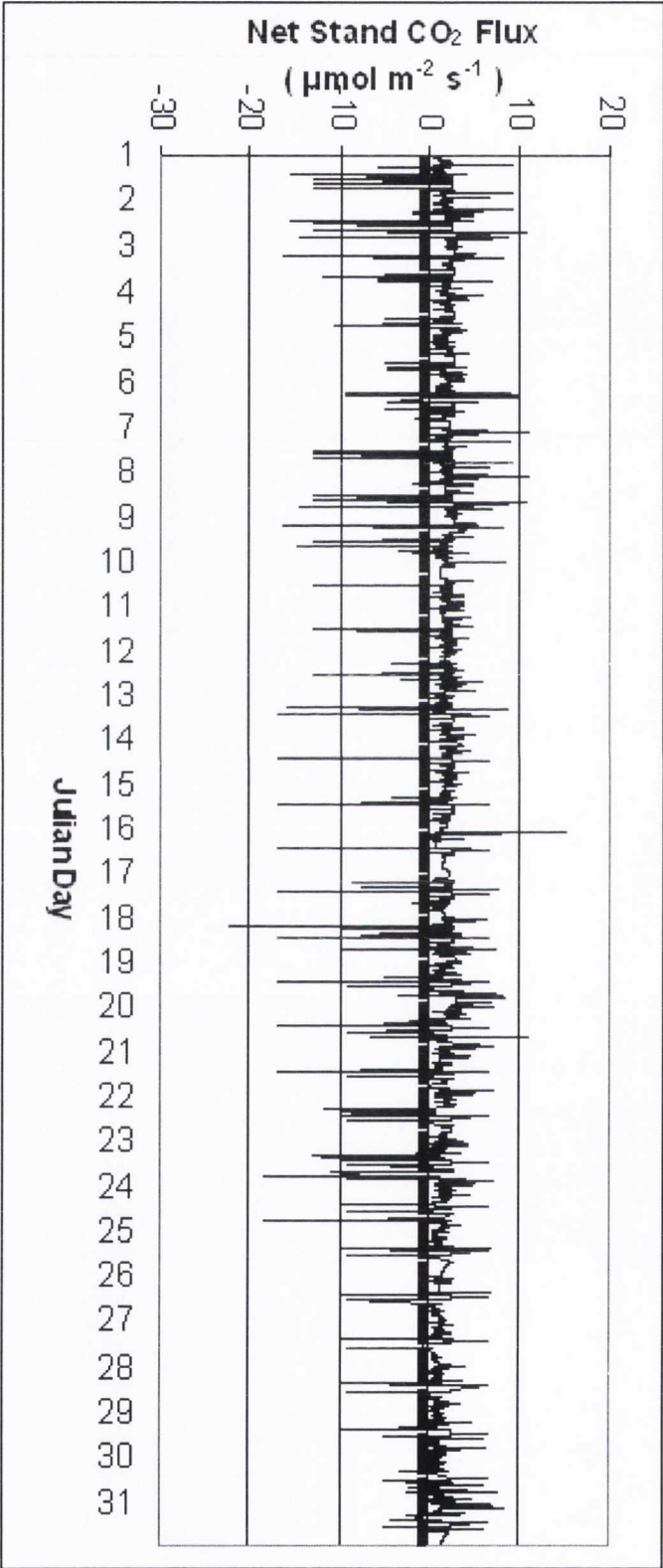
Appendix 16 : Net Stand CO₂ Flux measured above a homogenous *Miscanthus x giganteus* canopy at Oak Park Research Centre, Co. Carlow. Data collected from the 1st of November 2006 to the 30th of November 2006. Negative values indicate a net gain of CO₂ by the ecosystem; positive values indicate a net loss of CO₂ from the ecosystem.



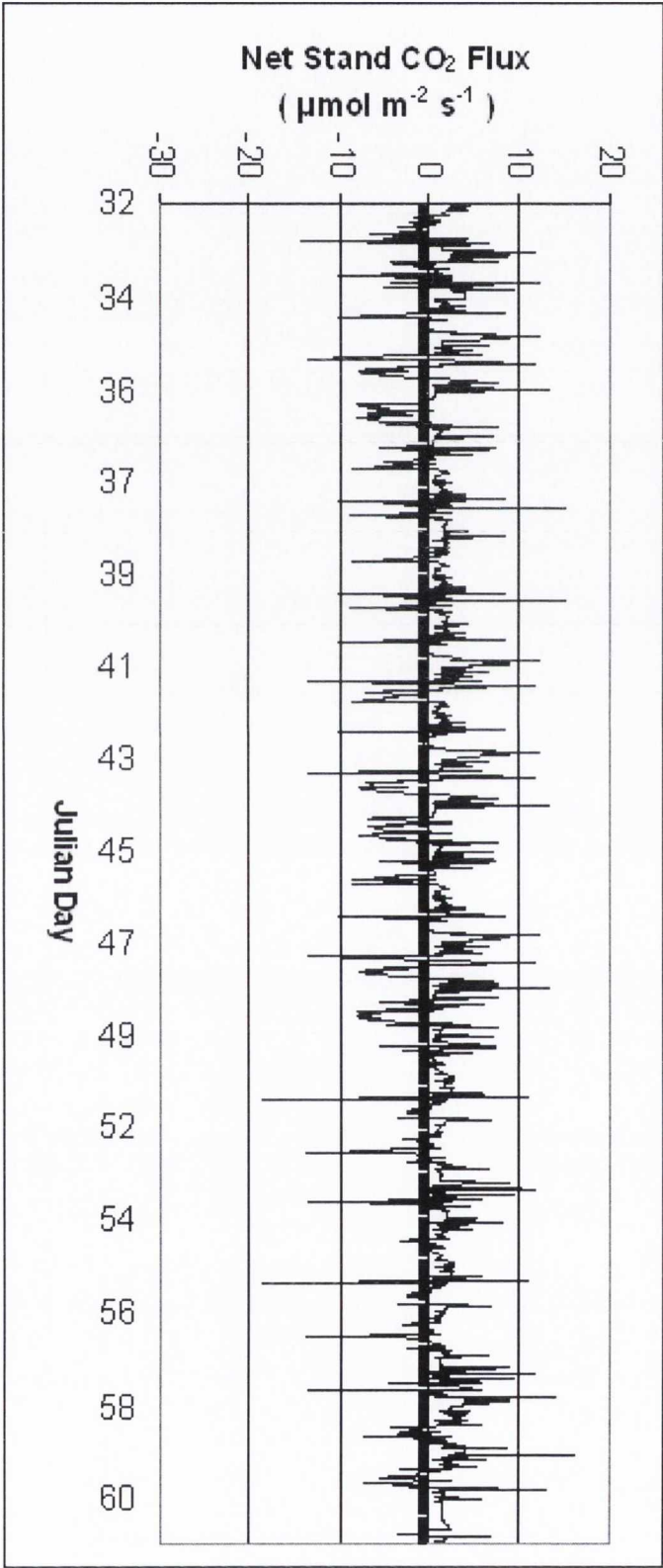
Appendix 17 : Net Stand CO₂ Flux measured above a homogenous *Miscanthus x giganteus* canopy at Oak Park Research Centre, Co. Carlow. Data collected from the 1st of December 2006 to the 31st of December 2006. Negative values indicate a net gain of CO₂ by the ecosystem; positive values indicate a net loss of CO₂ from the ecosystem.



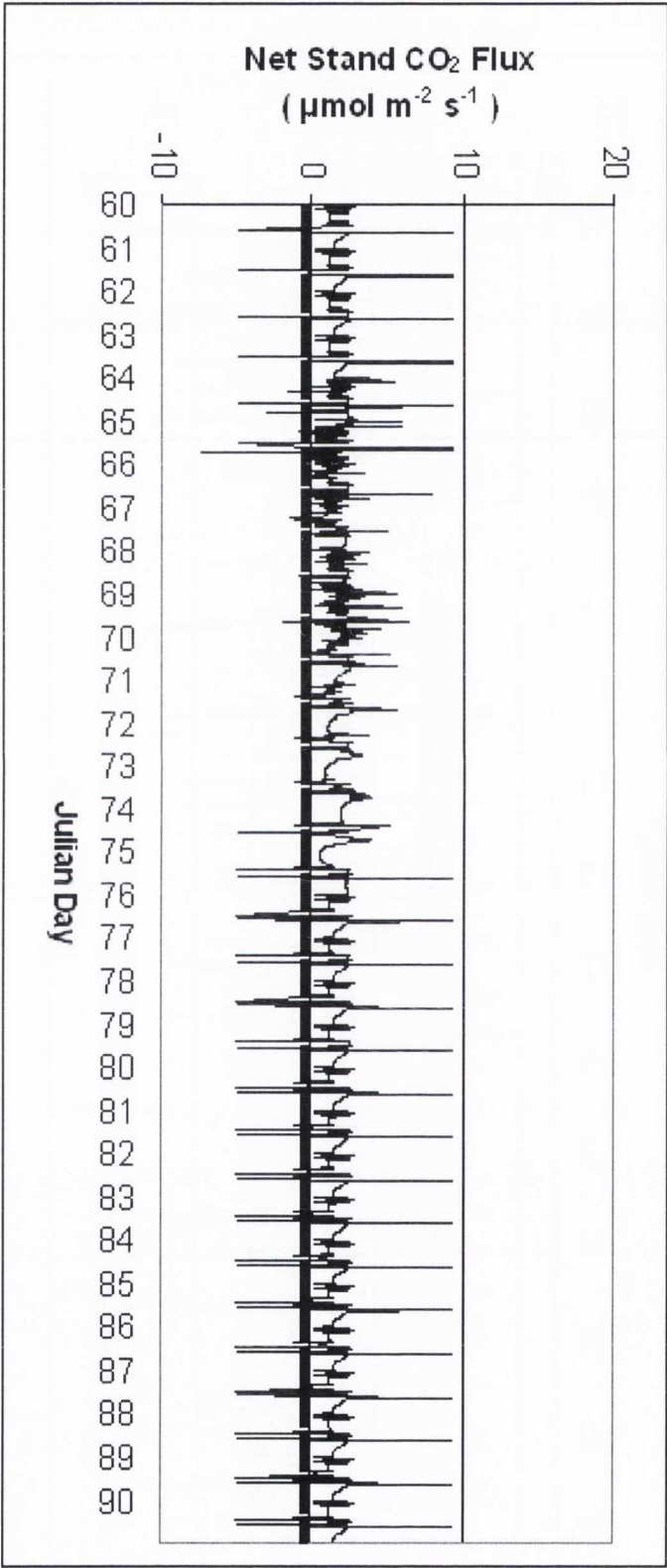
Appendix 18 : Net Stand CO₂ Flux measured above a homogenous *Miscanthus x giganteus* canopy at Oak Park Research Centre, Co. Carlow. Data collected from the 1st of January 2007 to the 31st of January 2007. Negative values indicate a net gain of CO₂ by the ecosystem; positive values indicate a net loss of CO₂ from the ecosystem.



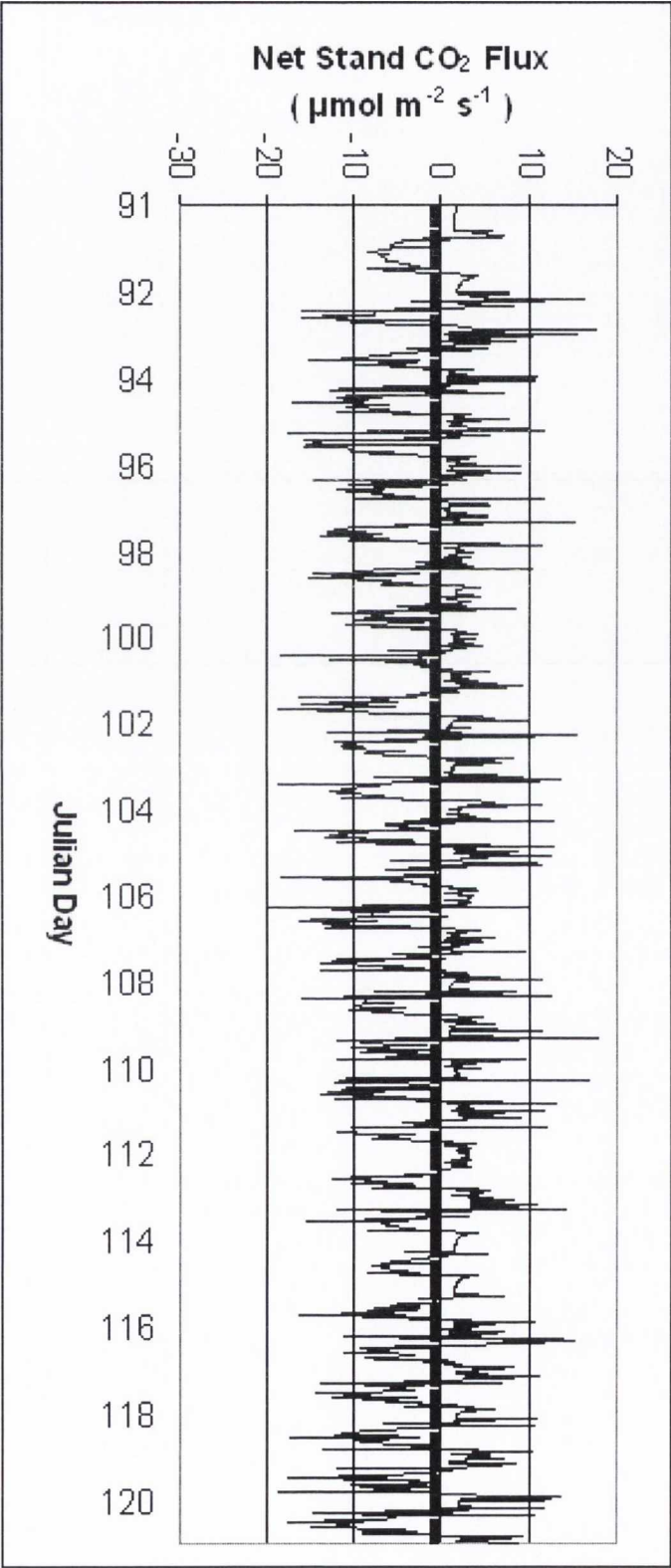
Appendix 19 : Net Stand CO₂ Flux measured above a homogenous *Miscanthus x giganteus* canopy at Oak Park Research Centre, Co. Carlow. Data collected from the 1st of February 2007 to the 28th of February 2007. Negative values indicate a net gain of CO₂ by the ecosystem; positive values indicate a net loss of CO₂ from the ecosystem.



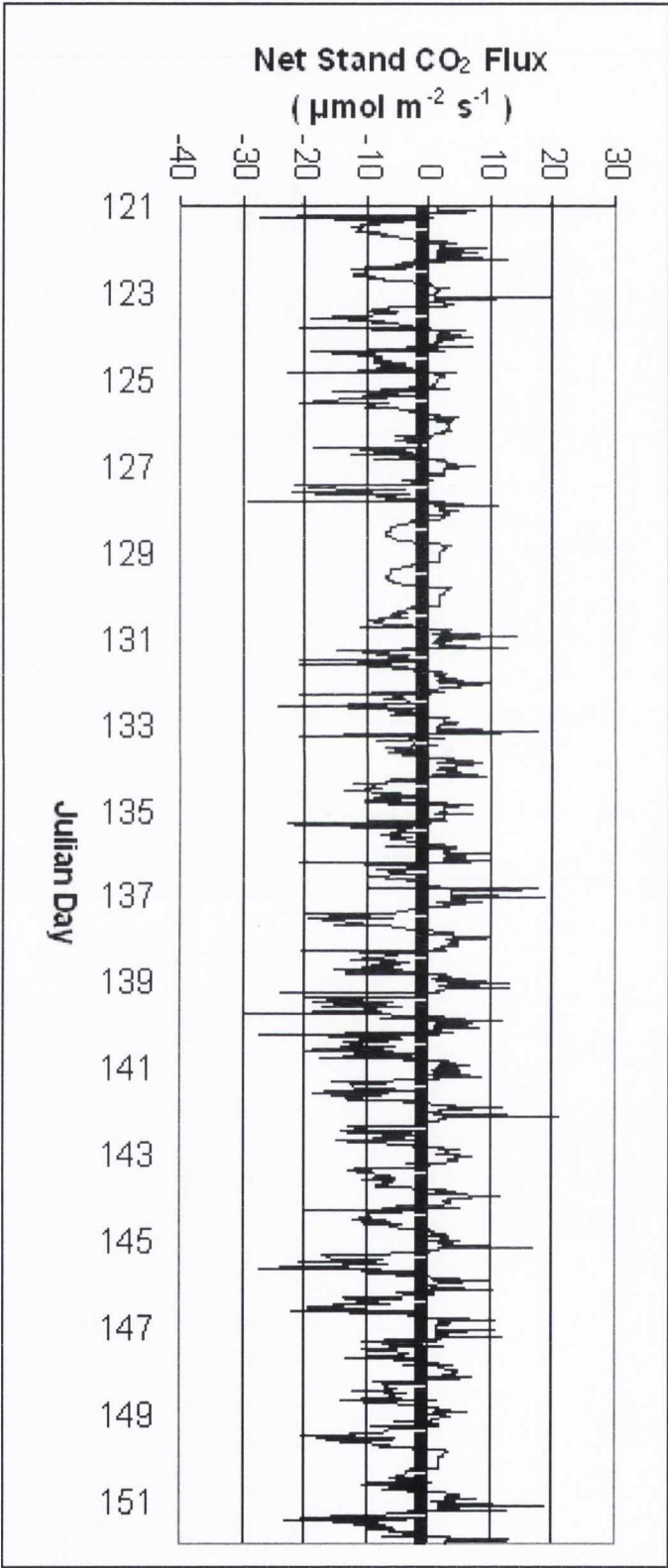
Appendix 20 : Net Stand CO₂ Flux measured above a homogenous *Miscanthus x giganteus* canopy at Oak Park Research Centre, Co. Carlow. Data collected from the 1st of March 2007 to the 31st of March 2007. Negative values indicate a net gain of CO₂ by the ecosystem; positive values indicate a net loss of CO₂ from the ecosystem.



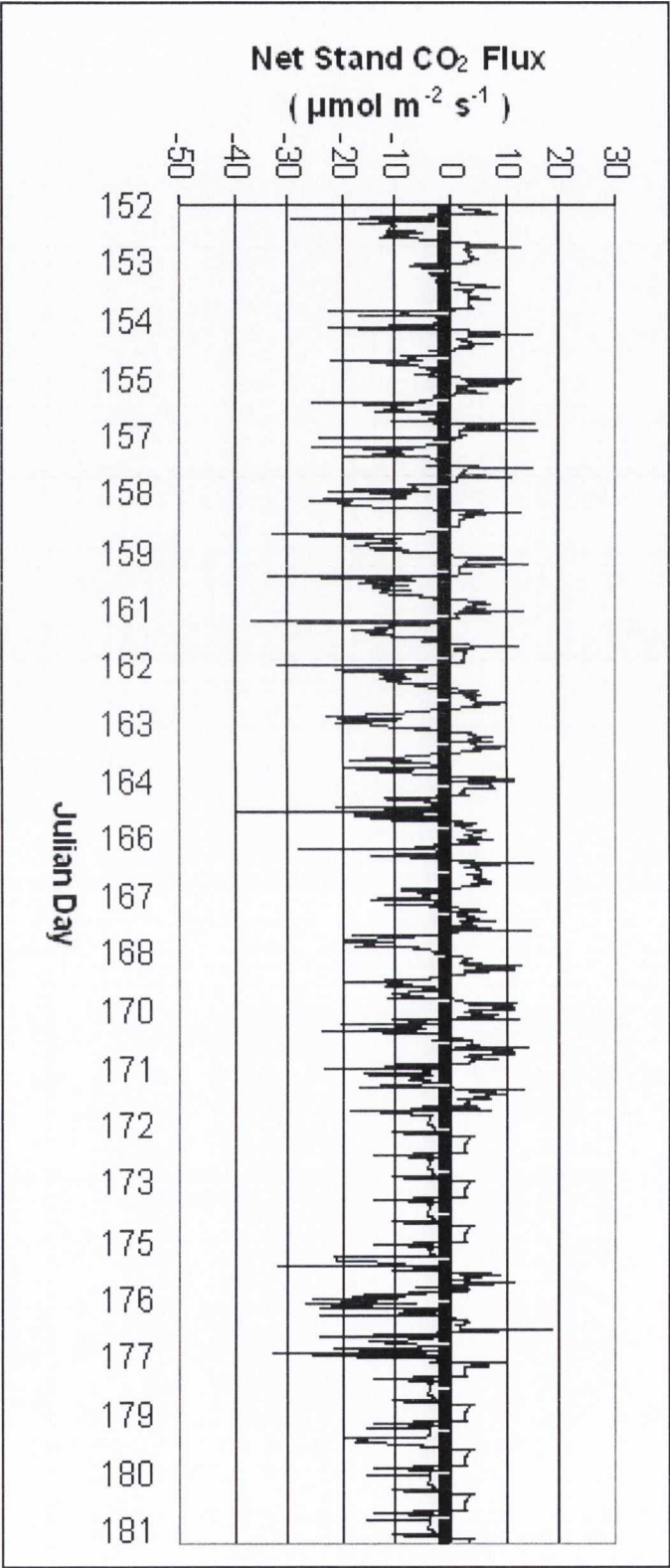
Appendix 21 : Net Stand CO₂ Flux measured above a homogenous *Miscanthus x giganteus* canopy at Oak Park Research Centre, Co. Carlow. Data collected from the 1st of April 2007 to the 30th of April 2007. Negative values indicate a net gain of CO₂ by the ecosystem; positive values indicate a net loss of CO₂ from the ecosystem.



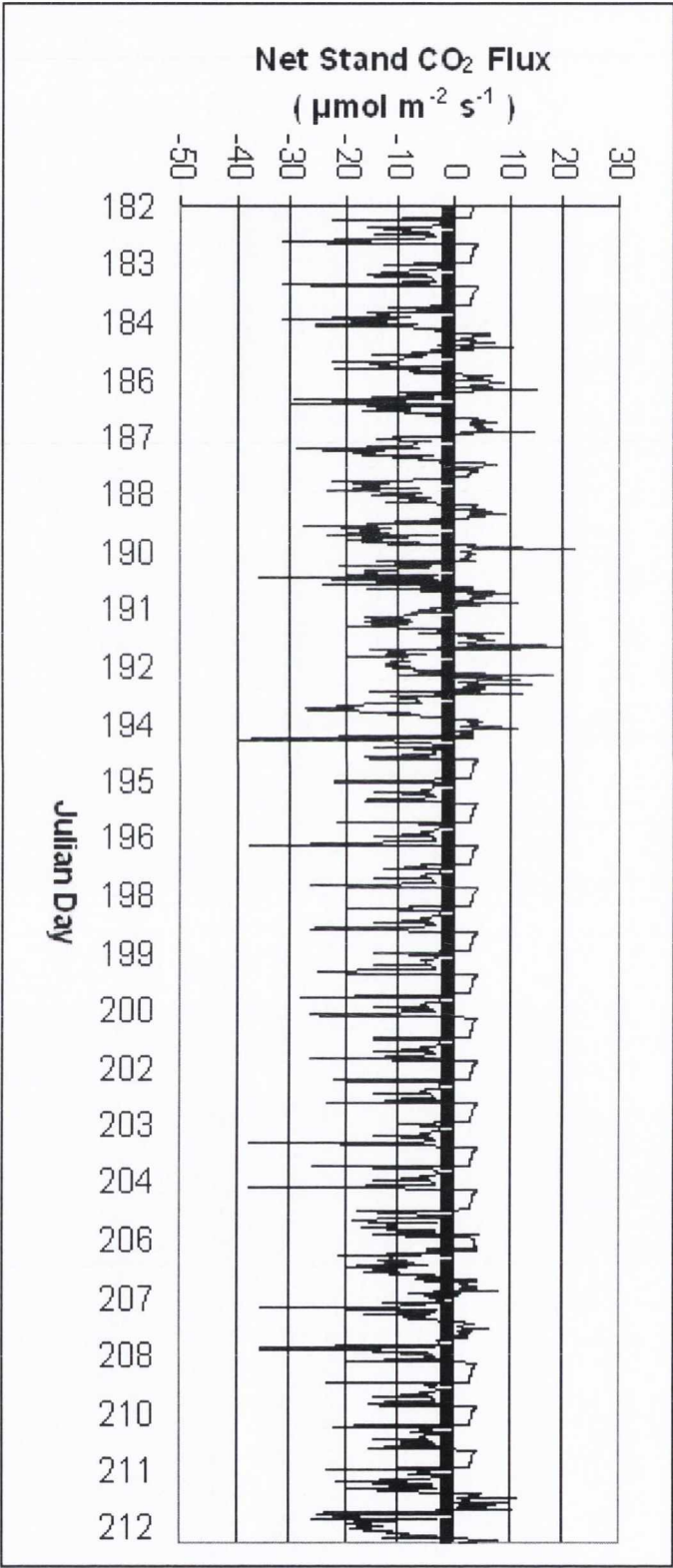
Appendix 22 : Net Stand CO₂ Flux measured above a homogenous *Miscanthus x giganteus* canopy at Oak Park Research Centre, Co. Carlow. Data collected from the 1st of May 2007 to the 31st of May 2007. Negative values indicate a net gain of CO₂ by the ecosystem; positive values indicate a net loss of CO₂ from the ecosystem.



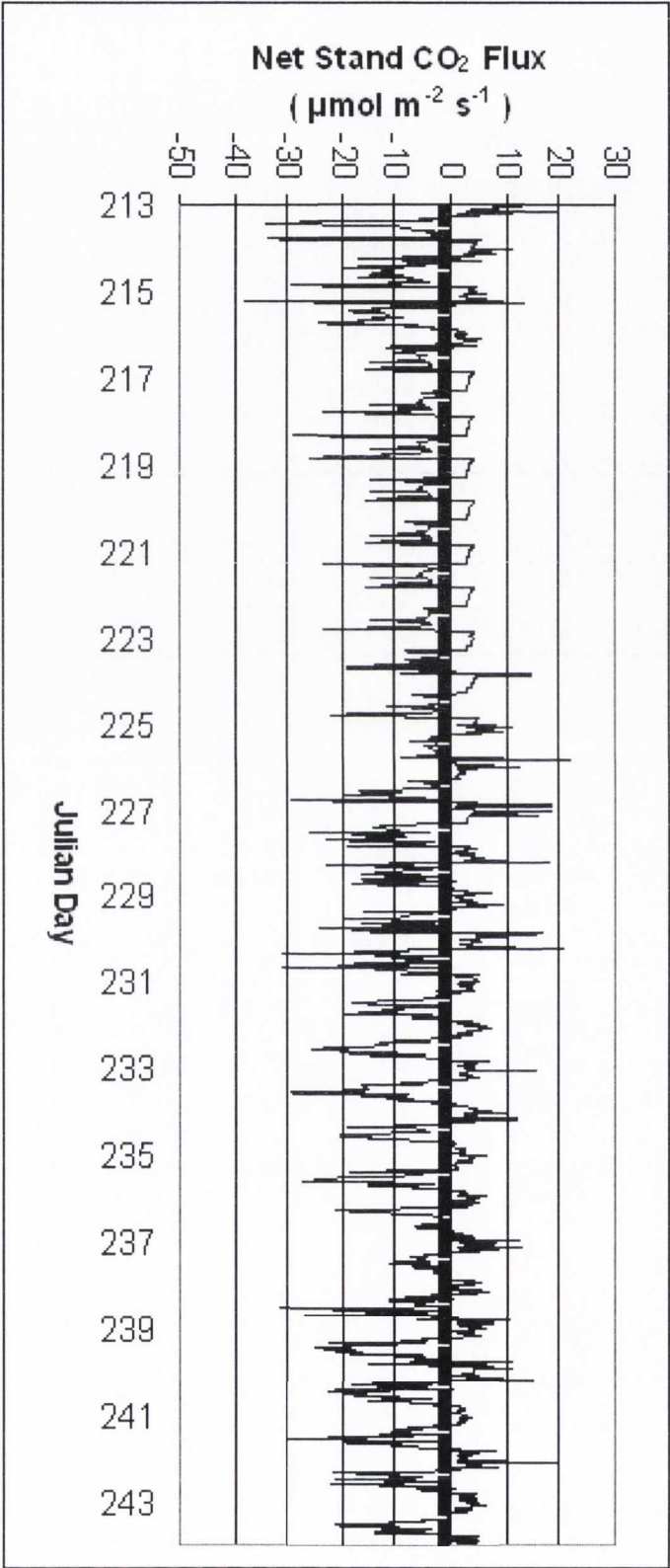
Appendix 23 : Net Stand CO₂ Flux measured above a homogenous *Miscanthus x giganteus* canopy at Oak Park Research Centre, Co. Carlow. Data collected from the 1st of June 2007 to the 30th of 2007. Negative values indicate a net gain of CO₂ by the ecosystem; positive values indicate a net loss of CO₂ from the ecosystem.



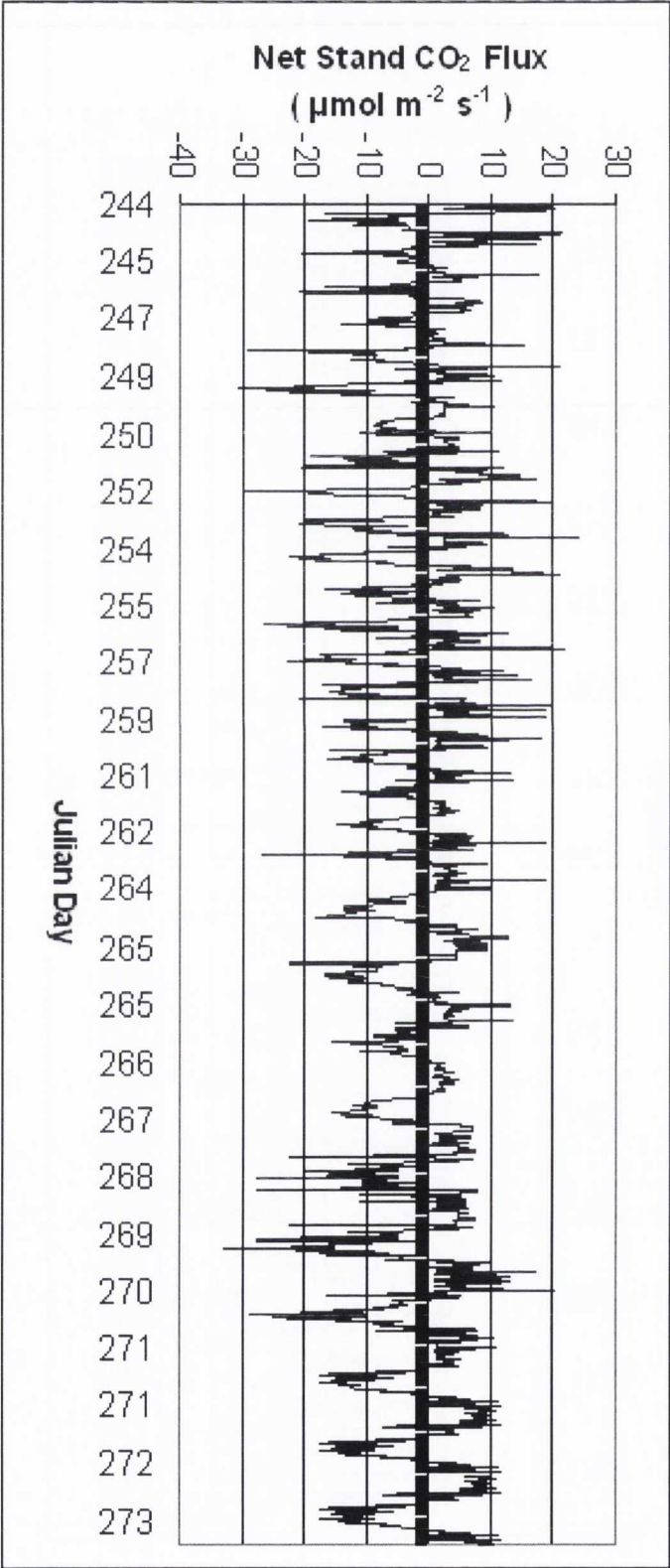
Appendix 24 : Net Stand CO₂ Flux measured above a homogenous *Miscanthus x giganteus* canopy at Oak Park Research Centre, Co. Carlow. Data collected from the 1st of July 2007 to the 31st of July 2007. Negative values indicate a net gain of CO₂ by the ecosystem; positive values indicate a net loss of CO₂ from the ecosystem.



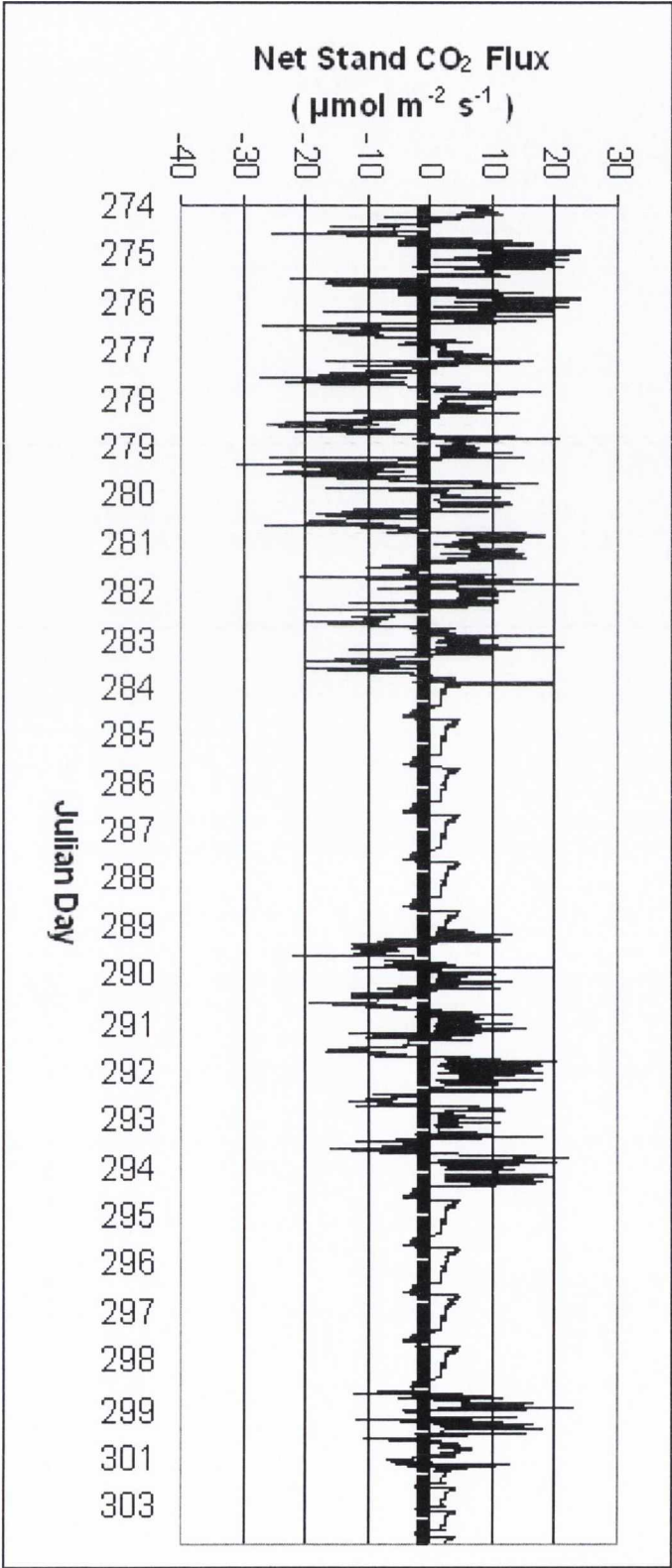
Appendix 25 : Net Stand CO₂ Flux measured above a homogenous *Miscanthus x giganteus* canopy at Oak Park Research Centre, Co. Carlow. Data collected from the 1st of August 2007 to the 31st of August 2007. Negative values indicate a net gain of CO₂ by the ecosystem; positive values indicate a net loss of CO₂ from the ecosystem.



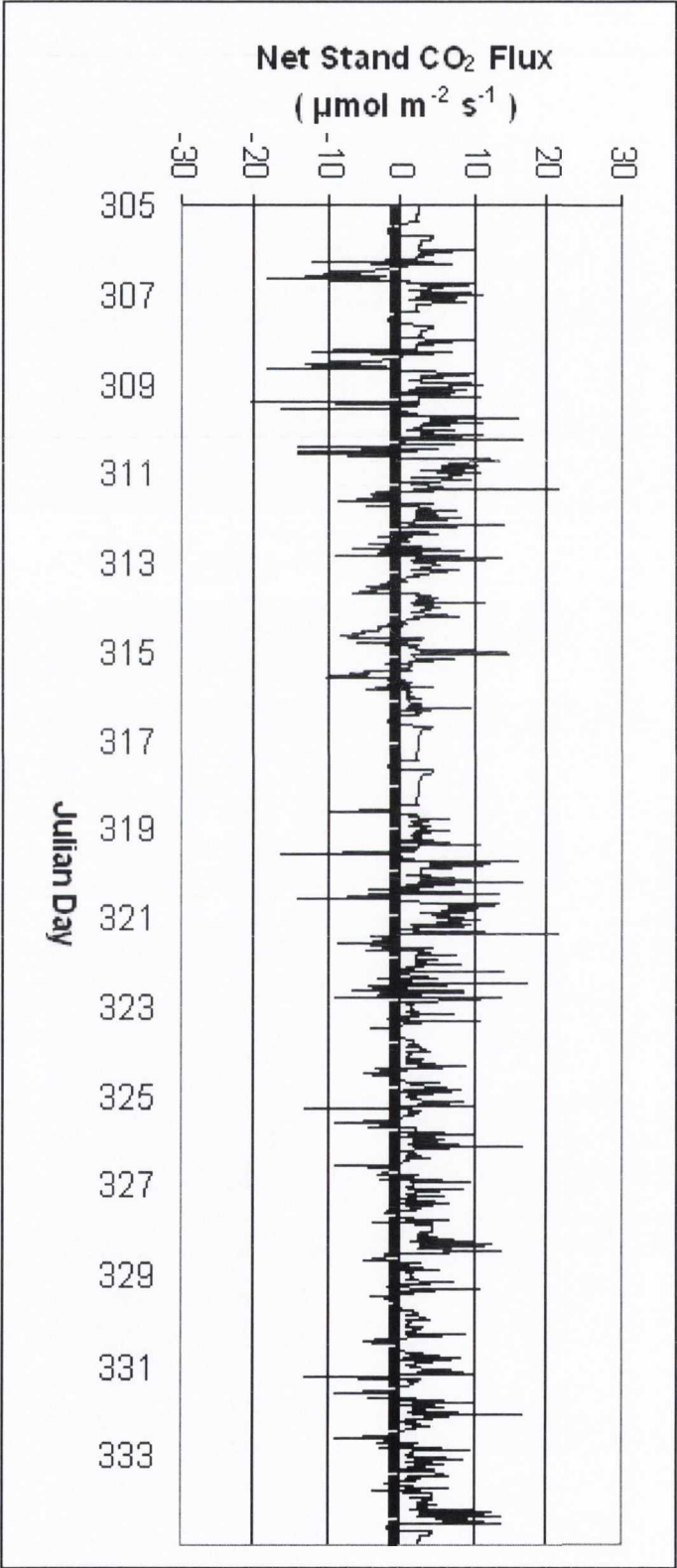
Appendix 26 : Net Stand CO₂ Flux measured above a homogenous *Miscanthus x giganteus* canopy at Oak Park Research Centre, Co. Carlow. Data collected from the 1st of September 2007 to the 30th of September 2007. Negative values indicate a net gain of CO₂ by the ecosystem; positive values indicate a net loss of CO₂ from the ecosystem.



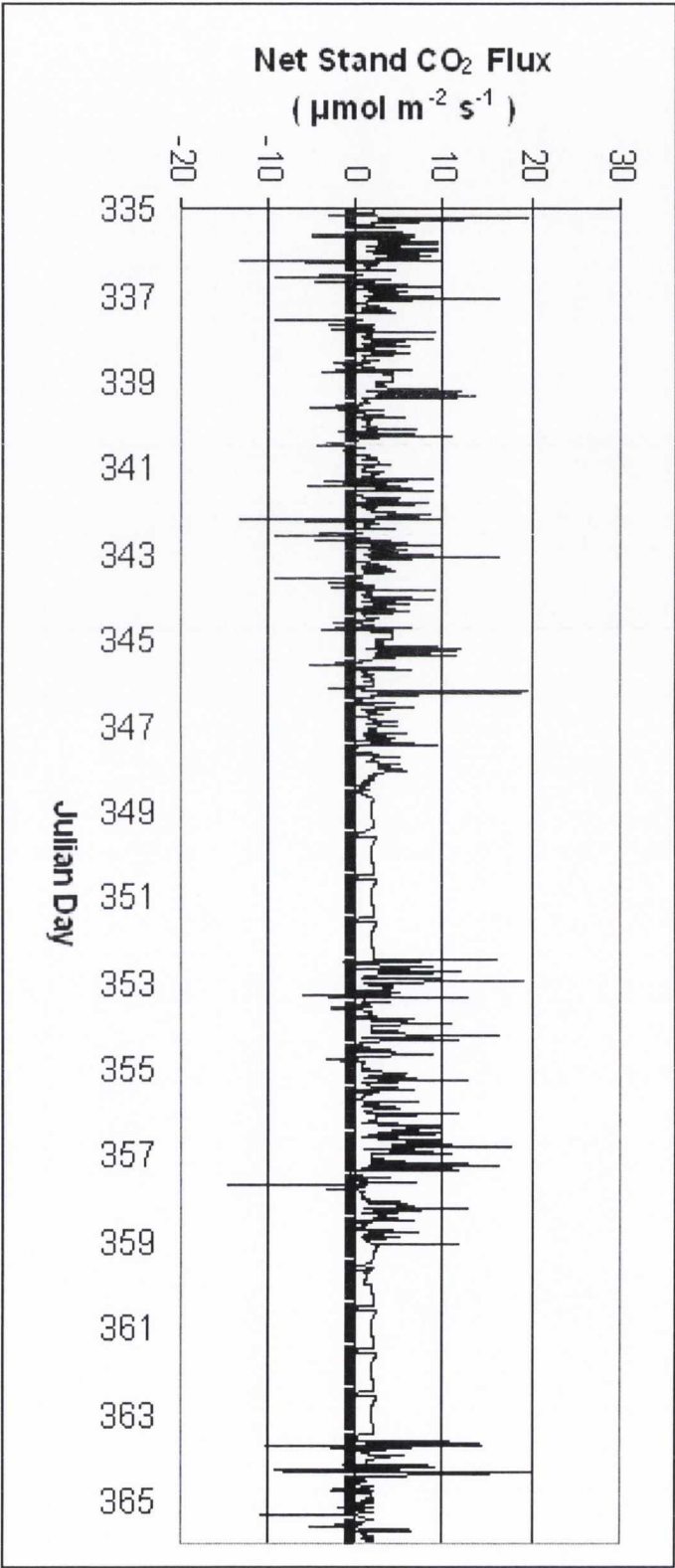
Appendix 27 : Net Stand CO₂ Flux measured above a homogenous *Miscanthus x giganteus* canopy at Oak Park Research Centre, Co. Carlow. Data collected from the 1st of October 2007 to the 31st of October 2007. Negative values indicate a net gain of CO₂ by the ecosystem; positive values indicate a net loss of CO₂ from the ecosystem.



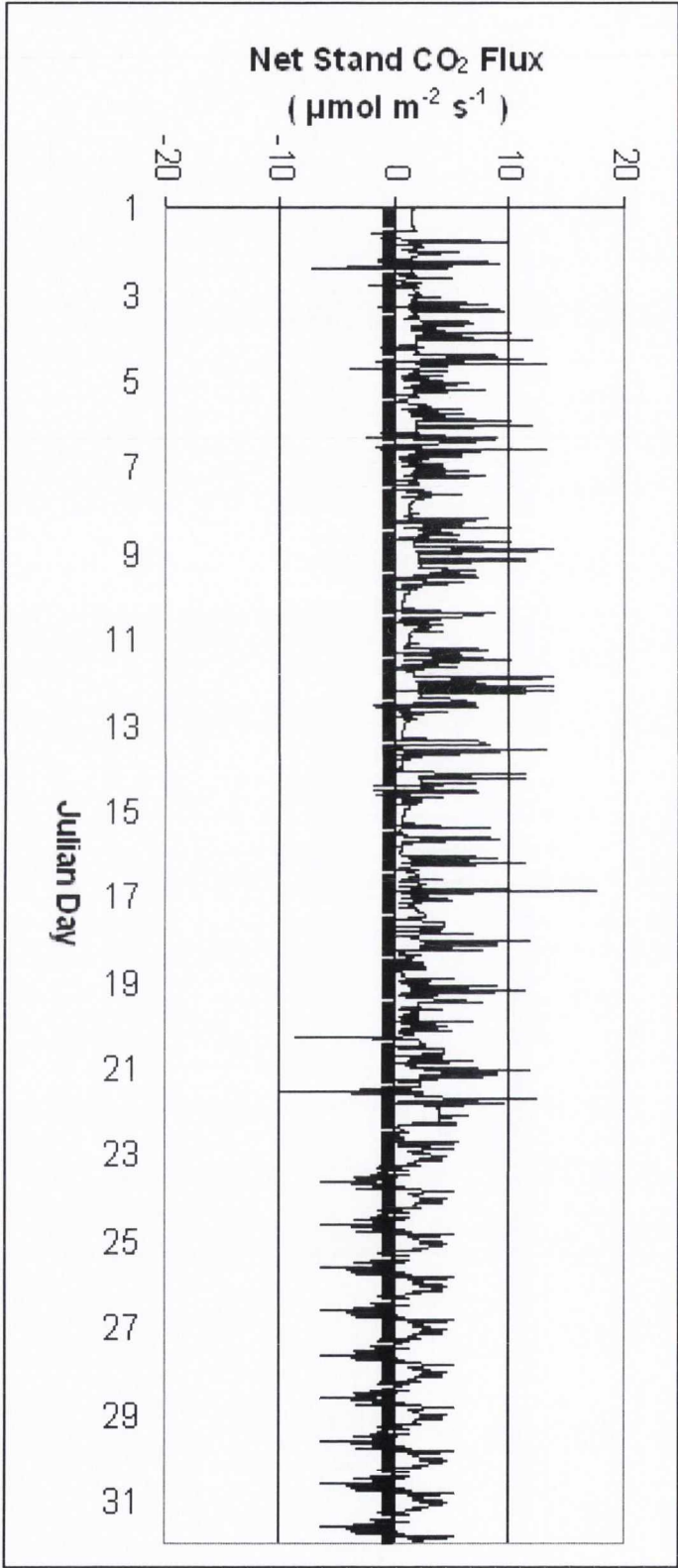
Appendix 28 : Net Stand CO₂ Flux measured above a homogenous *Miscanthus x giganteus* canopy at Oak Park Research Centre, Co. Carlow. Data collected from the 1st of November 2007 to the 30th of November. Negative values indicate a net gain of CO₂ by the ecosystem; positive values indicate a net loss of CO₂ from the ecosystem.



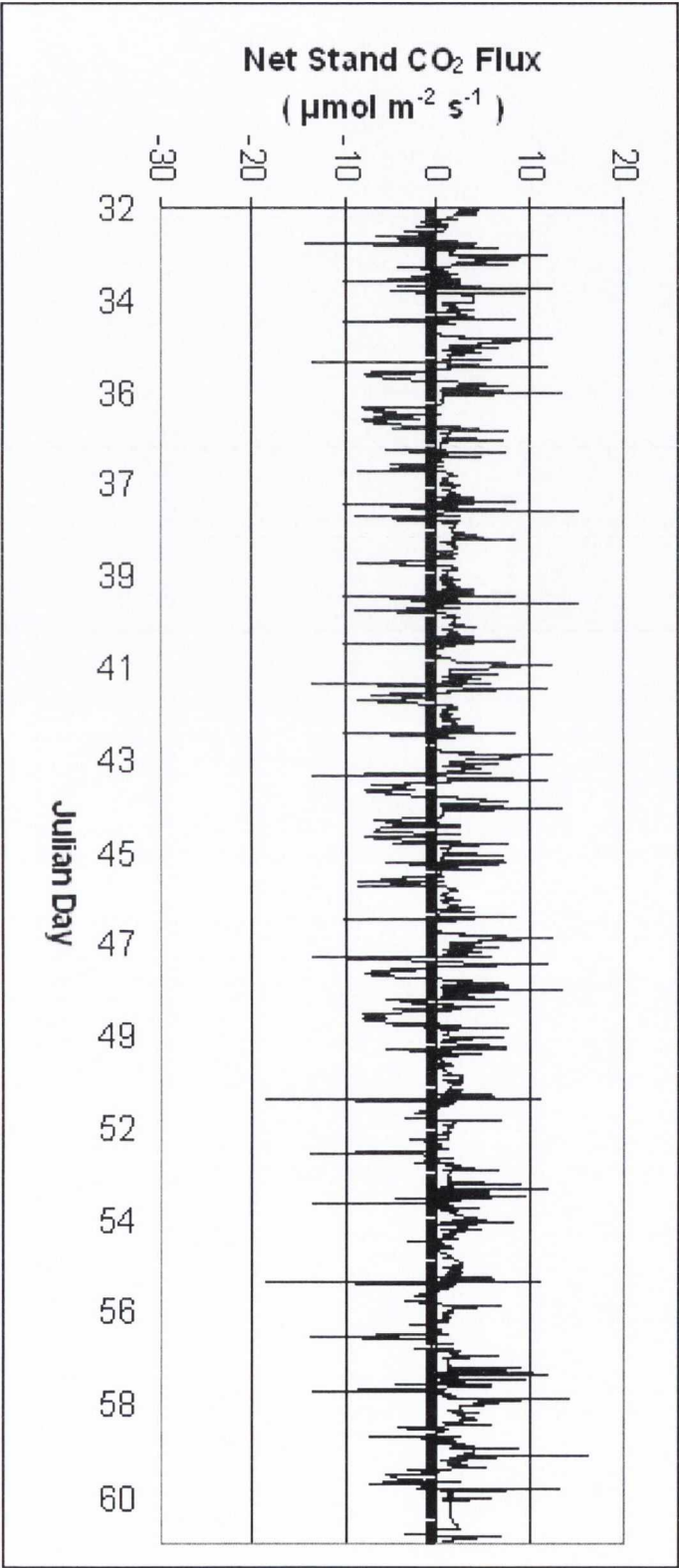
Appendix 29 : Net Stand CO₂ Flux measured above a homogenous *Miscanthus x giganteus* canopy at Oak Park Research Centre, Co. Carlow. Data collected from the 20071st of December 2007 to the 31st of December. Negative values indicate a net gain of CO₂ by the ecosystem; positive values indicate a net loss of CO₂ from the ecosystem.



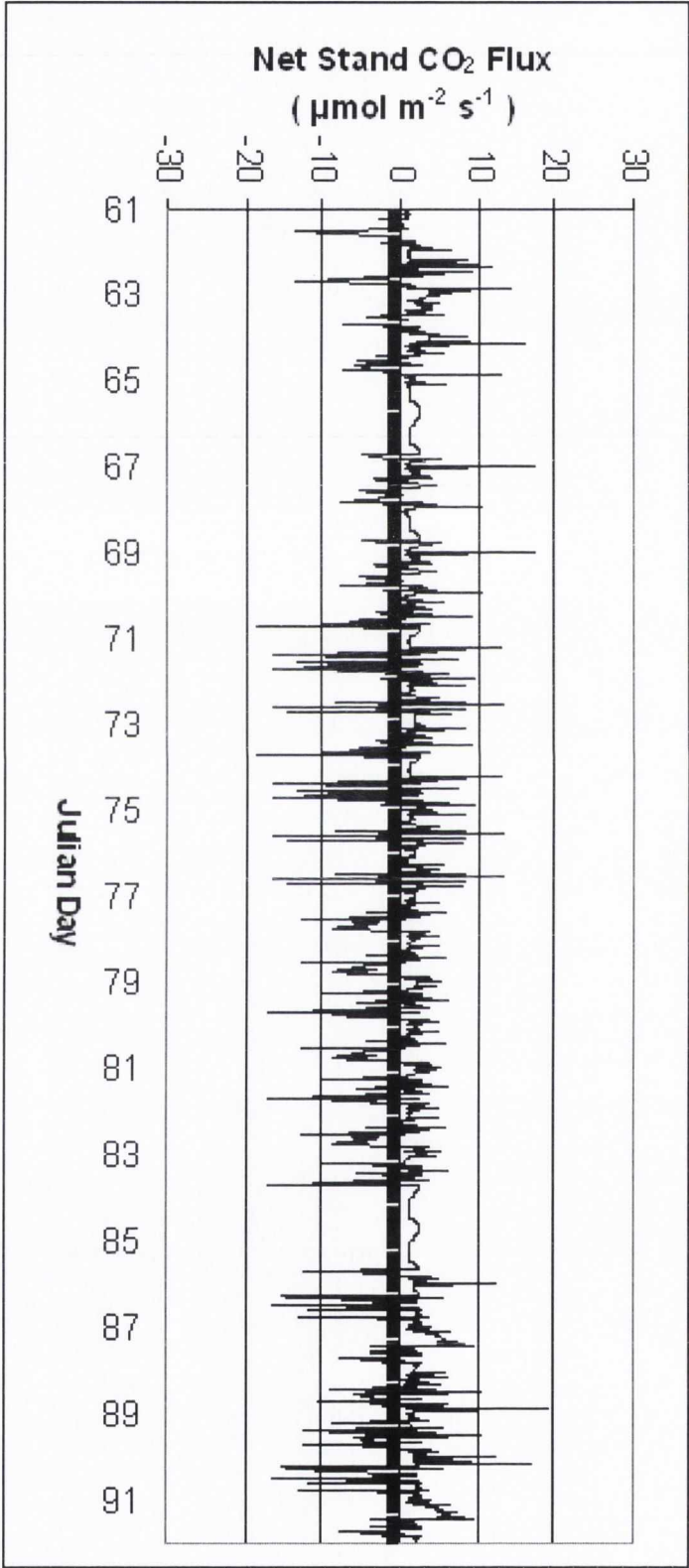
Appendix 30 : Net Stand CO₂ Flux measured above a homogenous *Miscanthus x giganteus* canopy at Oak Park Research Centre, Co. Carlow. Data collected from the 1st of January 2008 to the 31st of January 2008. Negative values indicate a net gain of CO₂ by the ecosystem; positive values indicate a net loss of CO₂ from the ecosystem.



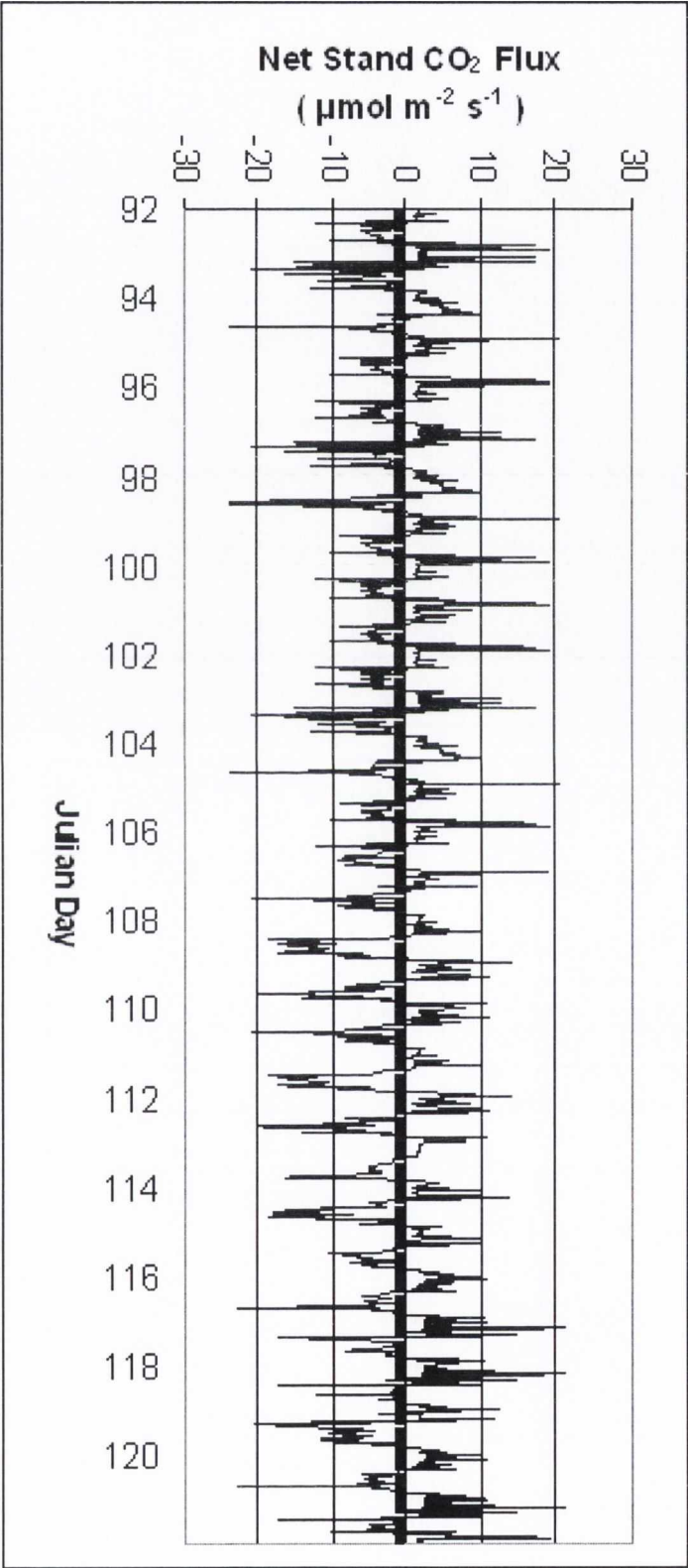
Appendix 31 : Net Stand CO₂ Flux measured above a homogenous *Miscanthus x giganteus* canopy at Oak Park Research Centre, Co. Carlow. Data collected from the 1st of February 2008 to the 29th of February 2008. Negative values indicate a net gain of CO₂ by the ecosystem; positive values indicate a net loss of CO₂ from the ecosystem.



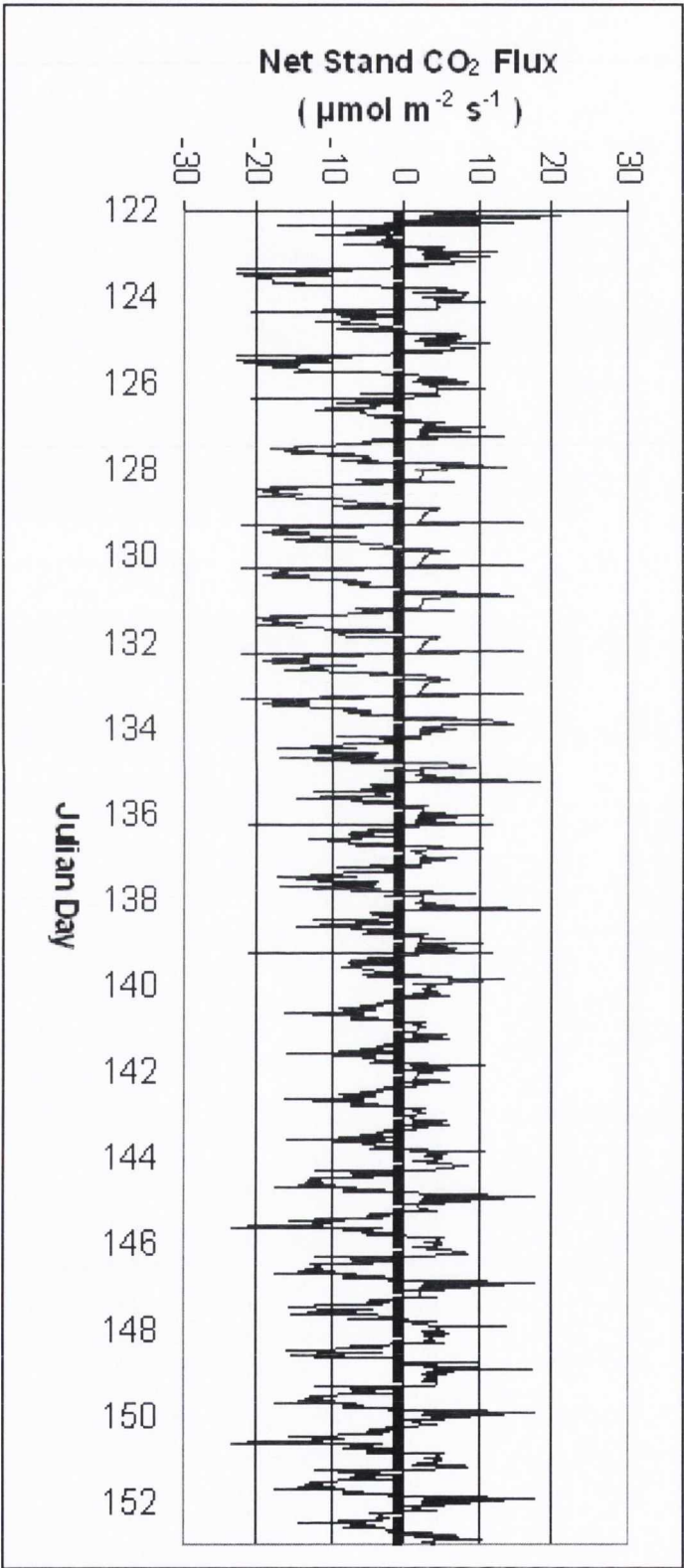
Appendix 32 : Net Stand CO₂ Flux measured above a homogenous *Miscanthus x giganteus* canopy at Oak Park Research Centre, Co. Carlow. Data collected from the 1st of March 2008 to the 31st of March 2008. Negative values indicate a net gain of CO₂ by the ecosystem; positive values indicate a net loss of CO₂ from the ecosystem.



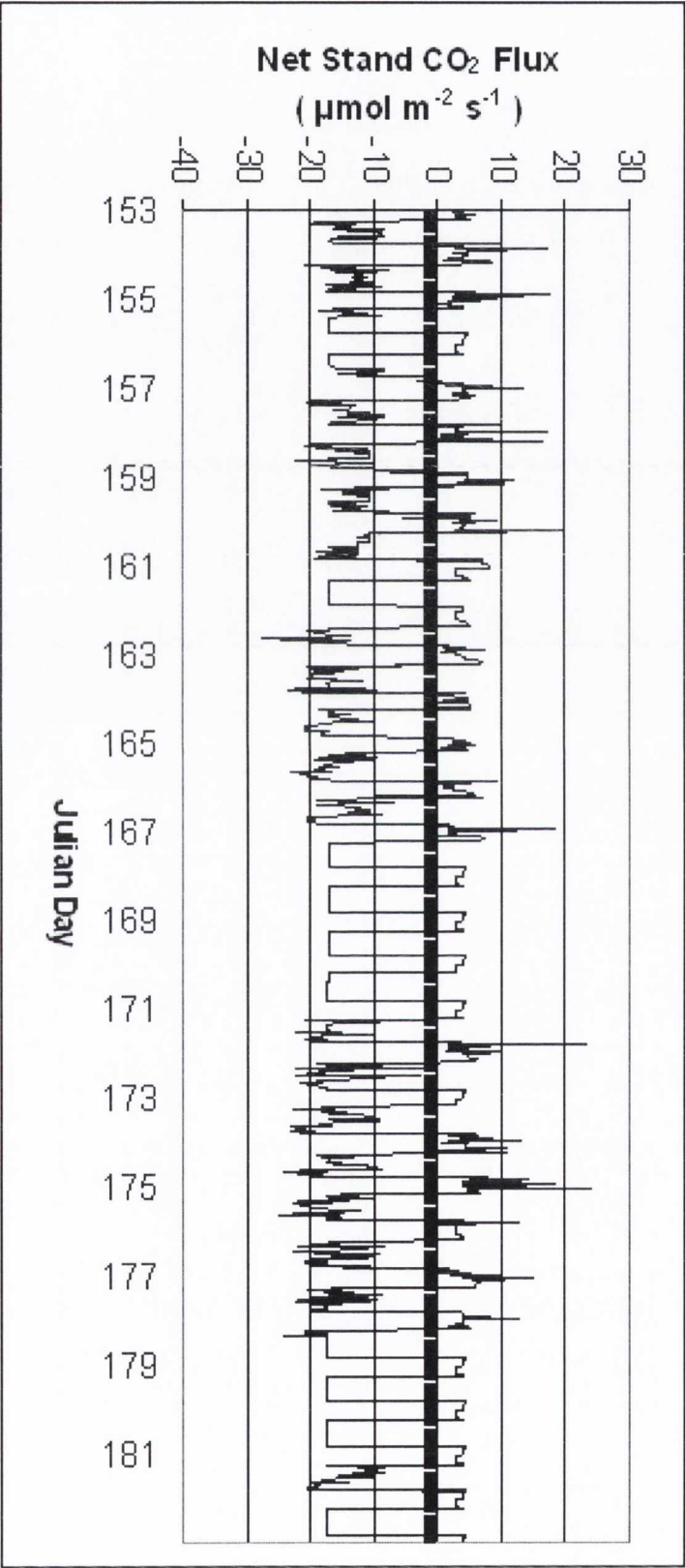
Appendix 33 : Net Stand CO₂ Flux measured above a homogenous *Miscanthus x giganteus* canopy at Oak Park Research Centre, Co. Carlow. Data collected from the 1st of April 2008 to the 30th of April 2008. Negative values indicate a net gain of CO₂ by the ecosystem; positive values indicate a net loss of CO₂ from the ecosystem.



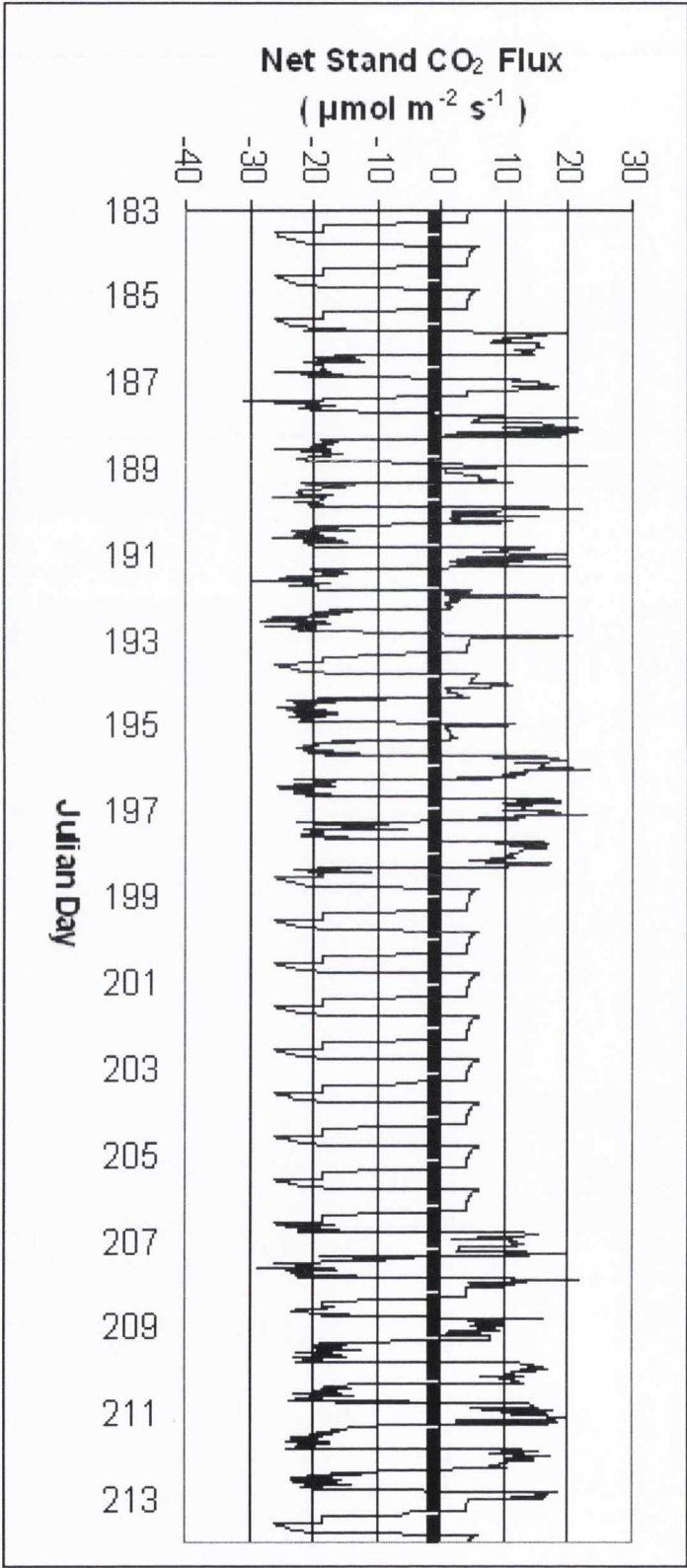
Appendix 34 : Net Stand CO₂ Flux measured above a homogenous *Miscanthus x giganteus* canopy at Oak Park Research Centre, Co. Carlow. Data collected from the 1st of May 2008 to the 31st of May 2008 Negative values indicate a net gain of CO₂ by the ecosystem; positive values indicate a net loss of CO₂ from the ecosystem.



Appendix 35 : Net Stand CO₂ Flux measured above a homogenous *Miscanthus x giganteus* canopy at Oak Park Research Centre, Co. Carlow. Data collected from the 1st of June 2008 to the 30th of 2008. Negative values indicate a net gain of CO₂ by the ecosystem; positive values indicate a net loss of CO₂ from the ecosystem.



Appendix 36 : Net Stand CO₂ Flux measured above a homogenous *Miscanthus x giganteus* canopy at Oak Park Research Centre, Co. Carlow. Data collected from the 1st of July 2008 to the 10th of August 2008. Negative values indicate a net gain of CO₂ by the ecosystem; positive values indicate a net loss of CO₂ from the ecosystem.



Appendix 37: Julian Day Calendar
 (source <http://modland.nascom.nasa.gov/browse/calendar.html>)

Leap years:
 (1988, 1992, 1996, 2000, 2004, 2008, 2012, ...)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	1	32	61	92	122	153	183	214	245	275	306	336
2	2	33	62	93	123	154	184	215	246	276	307	337
3	3	34	63	94	124	155	185	216	247	277	308	338
4	4	35	64	95	125	156	186	217	248	278	309	339
5	5	36	65	96	126	157	187	218	249	279	310	340
6	6	37	66	97	127	158	188	219	250	280	311	341
7	7	38	67	98	128	159	189	220	251	281	312	342
8	8	39	68	99	129	160	190	221	252	282	313	343
9	9	40	69	100	130	161	191	222	253	283	314	344
10	10	41	70	101	131	162	192	223	254	284	315	345
11	11	42	71	102	132	163	193	224	255	285	316	346
12	12	43	72	103	133	164	194	225	256	286	317	347
13	13	44	73	104	134	165	195	226	257	287	318	348
14	14	45	74	105	135	166	196	227	258	288	319	349
15	15	46	75	106	136	167	197	228	259	289	320	350
16	16	47	76	107	137	168	198	229	260	290	321	351
17	17	48	77	108	138	169	199	230	261	291	322	352
18	18	49	78	109	139	170	200	231	262	292	323	353
19	19	50	79	110	140	171	201	232	263	293	324	354
20	20	51	80	111	141	172	202	233	264	294	325	355
21	21	52	81	112	142	173	203	234	265	295	326	356
22	22	53	82	113	143	174	204	235	266	296	327	357
23	23	54	83	114	144	175	205	236	267	297	328	358
24	24	55	84	115	145	176	206	237	268	298	329	359
25	25	56	85	116	146	177	207	238	269	299	330	360
26	26	57	86	117	147	178	208	239	270	300	331	361
27	27	58	87	118	148	179	209	240	271	301	332	362
28	28	59	88	119	149	180	210	241	272	302	333	363
29	29	60	89	120	150	181	211	242	273	303	334	364
30	30		90	121	151	182	212	243	274	304	335	365
31	31		91		152		213	244		305		366

Appendix 37 (cont) : Julian Day Calendar
(source <http://modland.nascom.nasa.gov/browse/calendar.html>)

Regular years:
(2001, 2002, 2003, 2005, 2006, 2007, 2009, 2010, ...)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	1	32	60	91	121	152	182	213	244	274	305	335
2	2	33	61	92	122	153	183	214	245	275	306	336
3	3	34	62	93	123	154	184	215	246	276	307	337
4	4	35	63	94	124	155	185	216	247	277	308	338
5	5	36	64	95	125	156	186	217	248	278	309	339
6	6	37	65	96	126	157	187	218	249	279	310	340
7	7	38	66	97	127	158	188	219	250	280	311	341
8	8	39	67	98	128	159	189	220	251	281	312	342
9	9	40	68	99	129	160	190	221	252	282	313	343
10	10	41	69	100	130	161	191	222	253	283	314	344
11	11	42	70	101	131	162	192	223	254	284	315	345
12	12	43	71	102	132	163	193	224	255	285	316	346
13	13	44	72	103	133	164	194	225	256	286	317	347
14	14	45	73	104	134	165	195	226	257	287	318	348
15	15	46	74	105	135	166	196	227	258	288	319	349
16	16	47	75	106	136	167	197	228	259	289	320	350
17	17	48	76	107	137	168	198	229	260	290	321	351
18	18	49	77	108	138	169	199	230	261	291	322	352
19	19	50	78	109	139	170	200	231	262	292	323	353
20	20	51	79	110	140	171	201	232	263	293	324	354
21	21	52	80	111	141	172	202	233	264	294	325	355
22	22	53	81	112	142	173	203	234	265	295	326	356
23	23	54	82	113	143	174	204	235	266	296	327	357
24	24	55	83	114	144	175	205	236	267	297	328	358
25	25	56	84	115	145	176	206	237	268	298	329	359
26	26	57	85	116	146	177	207	238	269	299	330	360
27	27	58	86	117	147	178	208	239	270	300	331	361
28	28	59	87	118	148	179	209	240	271	301	332	362
29	29		88	119	149	180	210	241	272	302	333	363
30	30		89	120	150	181	211	242	273	303	334	364
31	31		90		151		212	243		304		365

Appendix 38: Weekly carbon fluxes over a *Miscanthus x giganteus* canopy at Oak Park Research Centre, Co. Carlow, from August 11th 2006 to August 10th 2007. Negative values indicate carbon uptake by the system; positive values indicate carbon release from the system.

Week No.	Month	GPP (g C wk ⁻¹)	R _{eco} (g C wk ⁻¹)	NEE (g C wk ⁻¹)
1	Aug	-96.66	21.20	-75.46
2	Aug	-72.57	17.40	-55.17
3	Aug	-72.19	15.94	-56.25
4	Sept	-56.32	20.63	-35.69
5	Sept	-52.02	20.67	-31.35
6	Sept	-37.80	18.94	-18.86
7	Sept	-38.65	17.69	-20.96
8	Oct	-38.03	18.19	-19.84
9	Oct	-37.51	18.67	-18.84
10	Oct	-30.08	16.90	-13.17
11	Oct	-20.68	14.25	-6.43
12	Oct	-11.41	11.68	0.27
13	Nov	-7.55	20.16	12.61
14	Nov	-4.31	18.88	14.57
15	Nov	-6.45	22.24	15.80
16	Nov	-1.72	26.64	24.92
17	Dec	-3.97	28.91	24.95
18	Dec	-3.96	21.15	17.19
19	Dec	-5.50	20.38	14.87
20	Dec	-7.94	25.51	17.57
21	Dec	-7.32	29.80	22.48
22	Jan	-5.52	28.81	23.29
23	Jan	-6.09	26.99	20.90
24	Jan	-5.97	21.32	15.35
25	Jan	-1.75	19.36	17.61
26	Jan	-4.09	17.10	13.01

Appendix 38 (cont) : Weekly carbon fluxes over a *Miscanthus x giganteus* canopy at Oak Park Research Centre, Co. Carlow, from August 11th 2006 to August 10th 2007. Negative values indicate carbon uptake by the system; positive values indicate carbon release from the system.

Week No.	Month	GPP (g C wk ⁻¹)	R _{eco} (g C wk ⁻¹)	NEE (g C wk ⁻¹)
27	Feb	-4.70	20.81	16.11
28	Feb	-1.66	25.22	23.56
29	Feb	-1.04	23.88	22.84
30	Feb	-0.89	23.26	22.37
31	Mar	-1.41	23.34	21.93
32	Mar	-1.96	22.38	20.42
33	Mar	-8.40	22.24	13.85
34	Mar	-18.35	8.73	-9.61
35	Apr	-20.15	7.70	-12.46
36	Apr	-13.49	8.04	-5.45
37	Apr	-21.64	10.73	-10.91
38	Apr	-23.35	7.26	-16.09
39	May	-18.72	9.28	-9.43
40	May	-27.30	11.05	-16.25
41	May	-27.00	8.03	-18.97
42	May	-19.86	12.00	-7.86
43	June	-42.38	11.06	-31.32
44	June	-22.57	13.69	-8.88
45	June	-27.05	7.95	-19.10
46	June	-28.54	8.45	-20.09
47	July	-39.06	9.07	-29.99
48	July	-32.56	10.91	-21.65
49	July	-28.22	9.51	-18.72
50	July	-34.29	9.30	-24.99
51	Aug	-32.99	8.69	-24.30
52	Aug	-17.58	5.39	-12.19

Appendix 39 : Weekly carbon fluxes over a *Miscanthus x giganteus* canopy at Oak Park Research Centre, Co. Carlow, from August 11th 2007 to August 10th 2008. Negative values indicate carbon uptake by the system; positive values indicate carbon release from the system.

Week No.	Month	GPP (g C wk ⁻¹)	R _{eco} (g C wk ⁻¹)	NEE (g C wk ⁻¹)
1	Aug	-23.89	12.14	-11.76
2	Aug	-35.81	10.80	-25.01
3	Aug	-30.02	10.03	-19.98
4	Sept	-24.30	14.79	-9.51
5	Sept	-28.20	12.84	-15.37
6	Sept	-22.06	12.17	-9.89
7	Sept	-50.87	21.80	-29.07
8	Oct	-34.24	47.39	13.15
9	Oct	-39.51	28.33	-11.18
10	Oct	-18.01	26.81	8.79
11	Oct	-12.45	42.19	29.74
12	Oct	-4.01	19.63	15.62
13	Nov	-9.33	22.29	12.96
14	Nov	-5.75	13.53	7.78
15	Nov	-4.65	19.21	14.56
16	Nov	-3.23	15.58	12.35
17	Dec	-2.68	18.22	15.54
18	Dec	-2.46	15.95	13.49
19	Dec	-0.79	14.01	13.22
20	Dec	-0.78	16.16	15.38
21	Dec	-1.89	12.70	10.81
22	Jan	-0.43	15.91	15.48
23	Jan	-0.29	14.43	14.14
24	Jan	-1.69	11.79	10.10
25	Jan	-3.24	8.72	5.48
26	Jan	-2.31	7.97	5.66

Appendix 39 (cont) : Weekly carbon fluxes over a *Miscanthus x giganteus* canopy at Oak Park Research Centre, Co. Carlow, from August 11th 2007 to August 10th 2008. Negative values indicate carbon uptake by the system; positive values indicate carbon release from the system.

Week No.	Month	GPP (g C wk ⁻¹)	R _{eco} (g C wk ⁻¹)	NEE (g C wk ⁻¹)
27	Feb	-3.56	7.19	3.63
28	Feb	-4.29	6.73	2.45
29	Feb	-3.93	7.75	3.81
30	Feb	-3.71	7.43	3.72
31	Mar	-3.80	6.30	2.50
32	Mar	-7.52	4.66	-2.86
33	Mar	-5.61	6.04	0.43
34	Mar	-6.82	8.32	1.50
35	Apr	-7.90	9.56	1.66
36	Apr	-14.78	8.55	-6.22
37	Apr	-20.69	8.78	-11.91
38	Apr	-11.28	14.07	2.79
39	May	-35.51	12.19	-23.33
40	May	-33.41	9.00	-24.41
41	May	-17.73	8.47	-9.26
42	May	-29.08	11.99	-17.09
43	June	-43.53	11.91	-31.62
44	June	-57.70	8.29	-49.41
45	June	-65.88	9.77	-56.11
46	June	-63.61	10.97	-52.63
47	July	-65.56	16.17	-49.39
48	July	-64.55	23.71	-40.84
49	July	-54.53	21.72	-32.81
50	July	-65.83	16.23	-49.60
51	Aug	-58.87	29.94	-28.93
52	Aug	-55.55	24.48	-31.07