CARBAL

Carbon gas balances in industrial cutaway peatlands in Ireland

Final report

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by the
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Executive Summary

Pristine peatlands play an important role in regulating the global climate by acting as long-term carbon (C) sinks. With the commencement of industrial peat harvesting, C gas dynamics are transformed and the peatland becomes a C source. To date, our knowledge of C dynamics in cutaway peatlands where harvesting has ceased and a new land use option has been developed is limited.

The Bord na Móna funded CARBAL project was initiated in 1999 to investigate carbon dioxide (CO_2) and methane (CH_4) exchange in a number of potential after uses for industrial cutaway peatlands. These were (1) commercial Sitka spruce afforestation, (2) natural regeneration to birch/willow woodland and (3) wetland creation.

A range of methodologies (biomass and chamber measurements) were employed in the study to provide an estimate of the annual C balance in each land use option. The results showed that the annual C stock increment in the Sitka spruce plantation was 7.92 tonnes C ha^{-1} yr^{-1} (above- and belowground biomass) for 2000-2002. Soil CO_2 emissions ranged from 6.64–6.70 t C ha^{-1} yr^{-1}, resulting in a net sink of 1.22–1.28 t C ha^{-1} for 2000-2002.

Annual C stock increment in the birch/willow woodland was estimated at 2.23 tonnes C ha^{-1} yr^{-1} (above- and belowground biomass) and between 7.17–7.79 t C ha^{-1} yr^{-1} was released through soil CO_2 emissions. This resulted in a net loss of 4.94–5.56 t C ha^{-1} yr^{-1} for 2000-2002.

The wetland vegetation communities in 2002 and 2003 exhibited considerable inter-annual variation in C dynamics primarily related to variation in rainfall and water table position. Rainfall at the study site was + 26.5 % and – 3.7 % of the long-term average for 2002 and 2003 respectively and strongly influenced the water table position. All communities were a source of C (CO_2 and CH_4) in both years. Mean losses ranged from 1.64-7.68 t C ha^{-1} yr^{-1}. Losses were higher in all communities in 2003.

There is considerable variation in the ability of the three land use options to sequester C. The reasons may be due to climatic variations, management practices, hydrology or edaphic factors. However, these results should be interpreted with caution and any global application of them to the industrial cutaways is not recommended Differences in hydrology, nutrient status, residual peat type and depth between industrial cutaways may result in other values than those reported here. Further research is required to determine whether the results reported herein may be applicable to other cutaways.

List of Abbreviations

C   Carbon

CH_4 Methane

CO_2 Carbon dioxide

DBH   Diameter breast height

DOC   Dissolved organic carbon

GHG   Greenhouse gases

GWP   Global Warming Potential

NEE   Net Ecosystem Exchange

N_2O Nitrous oxide

PAR   Photosynthetically Active Radiation

P_G Gross photosynthesis

R_{TOT} Ecosystem respiration

VGA   Vascular Green Area

Glossary of Terms

Acrotelm: Relatively aerobic zone above the water table in pristine peatlands that consists of the living parts of mosses and dead and poorly decomposed plant material. Has a relatively high hydraulic conductivity in comparison to the catotelm zone beneath it.

Afforestation: Planting of new forests on lands that have not been recently forested.

Carbon balance: The difference between the amount of C sequestered by the vegetation and that released during autotrophic and heterotrophic respiration, CH_4 emissions and losses of DOC. Positive values indicate that the ecosystem is a net C sink and negative values indicate ecosystem is a net C source.

Catotelm: Anaerobic zone found below the water table in pristine peatlands. As it is permanently saturated, decomposition rates are much lower than in the acrotelm. It is the main zone for methane production.

Emission: One-way movement of C gas from the peatland to the atmosphere.

Flux: Two-way directional flow of matter. In this study, positive flux values indicate a movement of C gas from the atmosphere into the peatland and negative values indicate a movement of C gas from the peatland to the atmosphere.

Greenhouse Effect: The insulating effect of atmospheric greenhouse gases (e.g. carbon dioxide, methane, etc.) that keeps the Earth's temperature warmer than it would be otherwise.

Methanogens: Microbial communities responsible for the production of methane.

Methanotrophs: Microbial communities responsible for the consumption of methane.

Photosynthesis: Process whereby CO_2 is sequestered by plants and converted into organic compounds using light as an energy source.

Respiration: Process whereby CO_2 is released to the atmosphere from the decomposition of plant litter, root exudates and peat by microbial communities (heterotrophic) and through the cellular breakdown of organic compounds by plants (autotrophic).

1 Introduction

David Wilson

1.1 Background

The rapid increase in the atmospheric concentration of greenhouse gases (GHGs), such as carbon dioxide (CO_2) and methane (CH_4), since circa. 1750 has been largely attributed to human activities such as the burning of fossil fuels and land use change (IPCC 2007). The relationship between GHG concentrations and global temperatures has been well established (Petit et al. 1999) and the increased concentration of these gases is believed to be responsible for the rise in the global mean temperature by around 0.76 °C over the last two hundred years (IPCC 2007). Whilst there is uncertainty in predicting future trends, the considered scientific consensus is that global temperatures could increase by up to 4 °C over the next 100 years (IPCC 2007) concurrent with projected increases of the C gases, CO_2 and CH_4, with possible grave implications for the global climate.

1.2 Pristine peatlands and CO_2

Since the last ice age, pristine or undamaged peatlands have accumulated significant stores of C and have played an important role in the regulation of the global climate. Pristine peatlands act as long term CO_2 sinks, primarily as a result of a persistently high water table. The high water table creates conditions whereby the amount of CO_2 fixed by the peatland vegetation during photosynthesis (P_G) is greater than that released during ecosystem respiration (R_{TOT}) and the net ecosystem exchange (NEE), defined as the difference between uptake and release (P_G - R_{TOT}), is positive. As plant litter and root exudates are deposited into the peat body, a proportion is oxidised as a result of heterotrophic respiration within the relatively aerobic zone (acrotelm) at the surface and released back to the atmosphere as CO_2. The amount released can vary considerably depending on the depth of the acrotelm, which in turn is determined to a large extent by the position of the water table (Nedwell and Watson 1995). Around 10% of primary productivity can be deposited below the water table in the anoxic catotelm (Clymo 1984) where the rate of decomposition occurs at a much slower rate than in the acrotelm (Clymo et al. 1998). CO_2 fluxes are strongly influenced by a range of abiotic and biotic factors, such as irradiation, temperature and physiological status of the vegetation, which are in turn subject to variation. As a result, P_G and R_{TOT} show considerable interannual variation (Shurpali et al. 1995; Lafleur et al. 2003) and a peatland can switch from being a CO_2 sink to a source in successive years.

1.3 Pristine peatlands and CH_4

Pristine peatlands are also a significant source of atmospheric CH_4 (Huttunen et al. 2003), accounting for around 23% of global emissions (Fung et al. 1991). CH_4 production is strongly influenced by environmental factors. The close relationship between CH_4 fluxes and the position of the water table has been reported in

numerous studies (Martikainen et al. 1995; Huttunen et al. 2003). Generally, a decrease in CH_4 emissions is associated with a lower water table (Saarnio et al. 1997). The position of the water table is central in influencing potential CH_4 production and oxidation rates, as it determines both the moisture and oxygen concentrations within the soil (Kettunen 2003).

The importance of vegetation to the production and transport of CH_4 has been well documented (Shannon and White 1994; Saarnio et al. 1997; Bubier et al. 2005). A high proportion of the CH_4 produced is a result of the breakdown of recently sequestered C in root exudates and plant litter. CH_4 production has been reported to be closely related to net primary production (Ström et al. 2003). However, the contribution of plants to CH_4 production can be ambiguous. In addition to providing substrates for the methanogenic bacteria populations, peatland plants also provide a means whereby the CH_4 produced in the anoxic zone can diffuse to the atmosphere without passing through the oxic zone.

Plant mediated transport is the most important pathway for CH_4 movement from the anoxic peat to the atmosphere accounting for between 50–97% of total CH_4 transported (Sebacher et al. 1985; Schimel 1995). In deep rooting wetland plants, the development of specialised internal gas transport structures, such as aerenchyma, facilitate the diffusion of oxygen from the leaves to the roots. However, this interconnected column of large air spaces also provides a conduit for CH_4 movement from roots deep in the anoxic substrate to the atmosphere (Dacey and Klug 1979).

1.2 Harvested peatlands

Although C gas exchange has been widely studied within pristine peatlands, much less is known regarding those dynamics in peatlands that have undergone considerable change through a combination of drainage and industrial peat extraction. Studies have shown that CO_2 dynamics undergo significant changes when a peatland is exploited for its fuel resource (Armentano and Menges 1986). In order to facilitate industrial extraction of the peat, drainage ditches are installed to lower the water table and reduce the moisture content of the peat from approximately 95% to 80% (Bord na Móna. http://www.bnm.ie). The installation of drainage ditches increases the depth of the oxic zone in the upper layers of the peatland (Waddington et al. 2001). Increased CO_2 emissions as a consequence of lower water table/moisture conditions have been reported for other peatland types (Silvola et al. 1996; Alm et al. 1999). After a number of years, the acrotelm layer at the surface is removed in order to facilitate the harvesting of the more highly decomposed peat within the catotelm and the surface of the peat is levelled. The removal of the acrotelm layer has a number of important effects on the system. It disrupts hydrological processes adding to the changes brought about by drainage i.e. peat shrinkage, compression, reduced hydraulic conductivity and pore size etc. (Price and Schlotzhauer 1999; Schlotzhauer and Price 1999; Price et al. 2003). However, removal of the photosynthesising vegetation also removes the C sequestering capability of the system (Waddington and Price 2000). Peat

harvesting transforms the peatland into a significant source of CO_2 (Rodhe and Svensson 1995; Sundh et al. 2000). However, the installation of drainage ditches and the removal of the vegetation layer at the surface results in reduced or zero CH_4 emissions (Sundh et al. 2000), partly as a result of a lowered water table, which produces a reduced anoxic zone and increased oxic zone (Strack et al. 2004) but primarily due to the absence of (1) easily degraded C substrates previously provided by the peatland vegetation and (2) the conduit for CH_4 that is provided by aerenchymatic plants. Other studies have shown that drained peatlands can act as small CH_4 sinks (for e.g. Martikainen et al. 1995) through increased activity of methanotrophic bacteria.

1.3 Industrial Cutaways

To date, only a small number of C gas studies have been carried out on peatlands where industrial harvesting has ceased and some new land use option has been developed. Work in Finland found that it was possible to return the C sink function in a relatively short period of time following the cessation of harvesting provided the water table was maintained close to the surface to minimise losses of CO_2 from degradation of the residual peat (Komulainen et al. 1999; Tuittila et al. 1999) and that recolonisation of the bare peat substrate occurred quickly. Rewetting and the return of vegetation also resulted in renewed emissions of CH_4 albeit at much lower levels than reported for nearby pristine peatlands (Komulainen et al. 1998; Tuittila et al. 2000a). However, studies in Canada demonstrated that the return of the C sink is difficult to achieve in the short term (Waddington and Price 2000; Waddington and Warner 2001).

There have been few published studies of gas exchange on afforested cutaways and so our knowledge of C dynamics in these ecosystems remains poor. Studies from forested peatlands suggest that GHG exchange undergoes fundamental changes with the installation of drainage ditches and the development of the tree stand (Minkkinen et al. 2002; von Arnold et al. 2005). Soil CO_2 emissions are increased but losses of CH_4 are likely to decrease considerably, although emissions from drainage ditches may still be significant (Minkkinen 1999; von Arnold et al. 2005).

1.4 Future land use options

The post-industrial use of the cutaway is largely determined by the residual peat type, underlying soil type and drainage conditions (Renou and Farrell 2005) as well as socio–economic considerations. Currently, Bord na Móna envisage that the main options for cutaways in Ireland in the future will be commercial afforestation, natural regeneration and wetland creation. In order to assess the impact of these land use changes on C gas exchange, three main sites were selected for study in the CARBAL project (Table 1.1).

Table 1.1 Characteristics of the CARBAL study sites.

	Commercial afforestation	Natural regeneration	Wetland creation
Location	Lullymore	Turraun	Turraun
Peat type	Woody fen/ Phragmites	Woody fen/ *Phragmites*	*Phragmites*
Peat depth	0.25 – 0.9 m	0.16 – 0.75 m	0 – 1.8 m
pH	ND	5.2[a]	4.5 – 7.9[a]
Vegetation	Sitka spruce	Birch, willow, soft rush	Common reed, cattail, canary grass, bog cotton, beaked sedge
Site age (yrs)	19	15[*]	12

[a](Rowlands 2001),
[*]Average age

1.5 Aims of the study

In the afforested Sitka spruce and natural generated sites, our aim was to;

(1) Estimate C input by the use of biomass measurements and the development of annual increment models.
(2) Measure C output (soil CO_2 emissions) at weekly-biweekly intervals using the chamber method.
(3) Examine the relationship between soil CO_2 emissions and environmental variables, such as soil temperature.
(4) Develop models based on the relationships at (3) to provide an estimate of the annual soil CO_2 emissions.
(5) Calculate the annual C balance in each land use option.

In the wetlands at Turraun, our aim was to;

(1) Measure CO_2 and CH_4 fluxes at weekly – biweekly intervals throughout the study period.

(2) Measure environmental variables, such as water table position, soil temperature, irradiation and vegetation composition concurrent with the measurement of gas fluxes.

(3) Examine the relationship between gas fluxes and environmental variables.

(4) Develop models based on the relationships at (3) to provide an estimate of annual gross photosynthesis (P_G), ecosystem respiration (R_{TOT}) and CH_4 emissions.

(5) Calculate the annual C balance.

2 Commercial afforestation

Kenneth A. Byrne, Raquel Cabral and Edward P. Farrell

2.1 Study site

The peatland at Lullymore, Co. Kildare (Lat. N 53º 17', Long. W 6º 56') was previously used for milled peat production. The residual peat is woody fen/*Phragmites* overlying a sub-peat mineral soil consisting of glacial till and clay. The site was afforested with Sitka spruce (*Picea sitchensis* (Bong) Carr.) in 1982 (19 years before the start of this study). No site preparation occurred prior to planting. Within the stand, parallel drains 1.3-1.5m wide and 15m apart were present, a legacy from the previous land use (Green et al. 2005).

2.2 Biomass estimation

The stand was estimated to be YC 18 based on Coillte data. The Current Annual Increment (CAI) was obtained from a Sitka spruce YC cohort model assuming a stand age of 19 years old (Black unpublished data). This CAI cohort model is used in conjunction with the CARBWARE model, which reports national C sequestration rates to the United Nations Framework Convention on Climate Change (UNFCC) on Land- Use, Land-Use Change and Forestry (LULUCF) and Kyoto Article 3.3 activities (Black and Farrell 2006). The uncertainty associated with the CAI estimate was based on Bayesian statistics using a validation data set from the CARBiFOR research project (Black and Farrell 2006).

2.3 Soil CO_2 sampling and analysis

Sixty sample plots were randomly established within the site. Each sample plot consisted of a circular plastic pipe (15cm diameter) that was inserted to a depth of 30cm into the peat at the beginning of the study with the intention of severing roots. As the pipe contained no living roots, the soil CO_2 efflux could be solely attributed to heterotrophic breakdown of the peat and forest floor. CO_2 sampling was carried out at weekly to biweekly intervals from January 2000 to December 2002 using portable infra-red gas analysers (EGM-2 and EGM-4; PP Systems, UK) connected to soil respiration chambers (SRC-1; PP Systems, UK) (Fig. 2.1). There was no understorey vegetation in the stand. Soil temperature was measured at 2cm depth in each plot after each CO_2 flux measurement.

Soil CO_2 emissions were related to soil temperature using an exponential response function (Eq. 1). This function was combined with a time series of soil temperature for 2000-2002 to estimate annual losses of C due to decomposition of the residual peat and forest floor.

$$\text{Soil } CO_2 = b_0 * \exp b_1 \qquad\qquad (\text{Eq.1})$$

Fig. 2.1 Infra-red gas analysers and soil respiration chambers employed in the measurement of soil CO_2 efflux at Lullymore, Co. Kildare and in the birch/willow woodland at Turraun, Co. Offaly.

2.4 Results

The net C balance of the Sitka spruce stand was estimated for the three years 2000-2002. This was done by calculating the net difference between the rate of C uptake in biomass and the rate of C loss due to decomposition of the residual peat and forest floor. Therefore the site is considered to be a C sink when the rate of C uptake in biomass exceeds the rate of C loss due to decomposition of the residual peat and forest floor.

The CAI cohort model estimated that the rate of C uptake in the Sitka spruce stand was 7.92 ± 1.06 tonnes CO_2-C ha^{-1} in 2002 (Table 2.1). At this stage of stand development there is unlikely to be significant inter-annual variation in the rate of C uptake and we assume the same value for 2000 and 2001. The rate of C loss due to decomposition of the residual peat, root biomass and forest floor was estimated to be 7.20, 7.17 and 7.24 t CO_2-C ha^{-1} in 2000, 2001 and 2002 respectively. Carbon inputs due to fine root turnover will reduce this by an estimated 0.5 t C ha^{-1} (Zerva et al. 2005). The net C balance is presented in Table 2.1 and suggests that the site was a net CO_2-C sink for 1.22 - 1.28 t CO_2-C ha^{-1} during 2000-2002.

Table 2.1. CO_2–C balance for the Sitka spruce stand, Lullymore, Co. Kildare for 2000-2002. Positive values indicate net ecosystem uptake. Negative values indicate net ecosystem loss.

	t C ha^{-1} yr^{-1}		
	2000	**2001**	**2002**
C uptake	7.92 ± 1.06	7.92 ± 1.06	7.92 ± 1.06
C loss	-6.70	-6.67	-6.64
Net CO_2 – C balance	**1.22**	**1.25**	**1.28**

3 Natural regeneration

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3.1 Study site

Turraun, Co. Offaly (Lat. N 53º 14' and 53º and 19' Long. W 7º 42' - 7º 48') was one of the first bogs to undergo industrial peat extraction in Ireland (Feehan and O'Donovan 1996). Prior to harvesting, the average depth of peat at Turraun was 6.2 m (Trodd 1998). When harvesting ceased in the 1970s, the residual peat depth ranged from 0-1.8m. Since that time, a wide range of vegetation communities have become established representing both dryland and wetland ecosystems (Rowlands 2001). The dryland communities are dominated by birch (*Betula* spp.) and willow (*Salix* spp.), ling heather (*Calluna vulgaris* L. (Hull)) and purple moor grass (*Molinea caerulea* (L.) Moench.)). The study site was located in an area of birch (~70%)/willow (~30%) woodland with an understory of bramble (*Rubus* spp.). Natural regeneration and the lack of silvicultural management, such as thinning, have produced a woodland with a high stocking rate (~ 6033 stems ha^{-1}), poor stem form (34% of the birch had two or more stems, many of which were crooked) and of variable age (average age 15 years).

3.2 Biomass estimation

The above-and belowground biomass of the stand was estimated using destructive harvesting. Ten trees representing the range in DBH values within the stand, including single and multiple stem trees, were harvested. Following felling, the fresh weight of all components (live branches, stemwood etc.) was recorded. Belowground biomass was estimated by the removal of all roots greater than 2 mm from a 2 m x 2m square marked from the centre of the each tree stump (Fig. 3. 1).

Fig. 3.1 Determination of below-ground biomass at Turraun, Co. Offaly.

The fresh weight of the roots was recorded. Sub-samples from above- and belowground components were taken to the laboratory and dried in an oven to produce an estimate of the dry weight of each tree. The fine root component (less than 2 mm) of the stand was estimated by random sampling to a depth of 15 cm using a corer (internal diameter). The samples were taken to the laboratory where the roots were removed from the surrounding peat matrix by washing. The samples were then dried to a constant weight at 105°C. Biomass functions (Eq.2) based on the relationship between the biomass components and DBH were developed using best-fit regression models, which were then upscaled to estimate the biomass stock per hectare. An estimate of the C stock (tonnes C ha^{-1}) in the stand was obtained by applying the C concentration factor to the biomass estimates. Mean annual increment (MAI) was calculated by dividing the C stock by the average age of the stand (15 years).

$$\ln Biomass = b_0 * \ln DBH + b \qquad (Eq.2)$$

3.3 Soil CO_2 sampling and analysis

Thirty sample plots were randomly established within the naturally regenerated birch / woodland. As with the sample plots at Lullymore, each plot consisted of a circular plastic pipe (15cm diameter) that was inserted to a depth of 30cm into the peat at the beginning of the study with the intention of severing roots. CO_2 sampling was carried out at weekly to biweekly intervals from January 2000 to December 2002 using the same portable infrared gas analysers employed at Lullymore (Fig. 2.1). Annual soil CO_2 emissions were calculated using the same method as used for the Sitka spruce site in Lullymore.

3.4 Results

The net C balance of the site was estimated for the three years 2000-2002 using the same approach as for the Sitka spruce stand in Lullymore. The biomass models estimated that the birch/willow woodland at Turraun accrued around 2.23 tonnes C ha^{-1} for 2002 (Table 3.1). We assume that the same value applies to 2000 and 2001. Given the highly variable nature of the site, in terms of age and composition, this estimate is likely to have a large uncertainty. The majority of the C was contained in the above ground component of the stand. The contribution of fine roots was negligible. The net loss of soil C due to decomposition of the residual peat, root biomass and forest floor was estimated to be 8.03, 8.04 and 7.42 t C ha^{-1} in 2000, 2001 and 2002 respectively. C inputs due to fine root turnover will reduce this by an estimated 0.25 t C ha^{-1}. The net C balance is presented in Table 3.1 and suggests that the site was a net C source of 4.94 - 5.56 t C ha^{-1} during 2000-2002.

Table 3.1 CO_2 – C balance for the birch / willow stand at Turraun, Co. Offaly for 2000-2002. Positive values indicate net ecosystem uptake. Negative values indicate net ecosystem loss.

	t C ha^{-1} yr^{-1}		
	2000	**2001**	**2002**
C uptake	2.23	2.23	2.23
C loss	-7.78	-7.79	-7.17
Net CO_2– C balance	**-5.55**	**-5.56**	**-4.94**

4 Wetland creation

David Wilson and Edward P. Farrell

4.1 Study site
In 1991, in order to improve the amenity and wildlife potential of the cutaway, a 60ha lake was constructed at Turraun, Co. Offaly, the drainage ditches were blocked, a mineral soil/peat bund was formed and the cutaway was reflooded. Within the wetlands a hydroseral gradient i.e. the sequence of vegetation communities, which occur during the transition from shallow open water at the edge of the lake to drier terrestrial ecosystems, has developed.

4.2 Microsites
At the beginning of the study, an extensive visual survey of all plant communities was undertaken to determine the dominant communities in the cutaway. Five microsites were subsequently selected to reflect the transition in plant communities from shallow water to drier terrestrial areas (Wilson 2005). Sample plots were established within the following;

- Common cattail (*Typha latifolia* L.) (Sample plots T1 and T2)
- Canary grass (*Phalaris arundinacea* L.) (P1 and P2)
- Bog cotton (*Eriophorum angustifolium* Honck) / beaked sedge (*Carex rostrata* Stokes) (EC1 – EC4)
- Soft rush (*Juncus effusus* L.)/Yorkshire fog (*Holcus lanatus* L.) (JH1 – JH4)
- Bare peat (BP1 – BP4)

Although it is extensively found within the wetlands, common reed (*Phragmites australis* (Cav.) Steud.) cannot be easily studied using chamber methods. Each sample plot consisted of a stainless steel collar (60 x 60 cm) that was inserted to a depth of 30cm into the peat prior to the start of the study (Fig. 4.1). Each collar was topped by a 4cm wide and 3cm deep channel that was filled with water to provide an airtight seal during gas measurements. Wooden walkways were constructed around each of the collars to minimise damage to the soil surface and plant cover and avoid compression of the peat during gas sampling.

Fig.4. 1 Stainless steel collars and wooden boardwalk in the bare plot microsite at Turraun wetlands, Co. Offaly.

4.3 CO$_2$ sampling

We employed the static chamber method to measure C0$_2$ and CH$_4$ fluxes (Fig. 4.2). Each chamber consisted of a polycarbonate chamber (60 x 60 x 33cm) equipped with a battery-operated fan, which ensured that the air within the chamber headspace was mixed. CO$_2$ concentration (ppmv) in the chamber headspace was measured with a portable CO$_2$ analyser (EGM-2 and 4) (PP Systems. UK) and Photosynthetically Active Radiation (PAR) (μmol m^{-2} s^{-1}) was measured by a quantum sensor (PAR-1. PP Systems) located at the top of the chamber.

CO$_2$ fluxes were measured between April 2002 and December 2003. Light and dark chambers were used to measure instantaneous net ecosystem exchange (NEE) in light and in dark. The measurement in the dark was also used as an estimate for total ecosystem (autotrophic and heterotrophic) respiration (R$_{TOT}$). Gross photosynthesis (P$_G$) was estimated as the sum of both measurements. We applied positive flux values to indicate that CO$_2$ uptake by the vegetation was greater than that lost through respiration. Conversely, negative values were applied for a net loss of CO$_2$ to the atmosphere.

Fig. 4. 2 Static light chamber used to measure CO$_2$ fluxes at Turraun wetlands, Co. Offaly. Extension chambers were used with the taller vegetation communities.

4.4 Environmental variables

Concurrent with the chamber measurements, soil temperatures at 2, 5, 10, 20 and 30cm depths were taken at each of the collars with a soil temperature probe (ELE International, UK). At the same time, air temperature (°C) and PAR values within the chamber were recorded. Water table height relative to the soil surface was also measured in perforated plastic pipes inserted into the peat at the beginning of the study.

A weather station (ELE International, UK) was located within the bog cotton/beaked sedge community and an averaged hourly time series of soil temperature at 2, 5, 10 and 20cm depths, wind speed and rainfall (mm) were recorded. Solar radiation (W m^{-2}) was measured by a pyranometer and converted into quantum sensor units (µmol m^{-2} s^{-1}) by comparison of simultaneous readings between the pyranometer and the quantum sensor from the chamber over a range of radiation values (Tuittila et al. 1999). Data loggers were also located within each of the microsites and recorded soil temperatures at 2, 5, 10 and 20cm depths.

4.5 CH$_4$ sampling

CH$_4$ measurements took place between July 2002 and December 2003 and were carried out at 1-2 week intervals. Gas samples were collected using the static chamber method (Crill 1991) (Fig. 4.3), which consisted of a polycarbonate chamber (60 x 60 x 20cm) equipped with a battery-operated fan, which mixed the air within the chamber headspace.

Fig. 4.3 Static chamber used to measure CH$_4$ fluxes at Turraun wetlands, Co. Offaly. Extension chambers were used within the taller vegetation communities.

Four 40ml samples were withdrawn into 60ml polypropylene syringes from the chamber headspace at 5-minute intervals over a 20-minute period. At the same time, air temperature inside the chamber, soil temperature at 2, 5, 10, 20 and 30cm depths and water table depth outside the chamber were recorded. The CH$_4$ concentration of each gas samples was determined within 24 hours of collection using a gas chromatograph (Shimadzu GC-14-B) equipped with a flame ionisation detector (FID). CH$_4$ fluxes (mg CH$_4$ m^{-2} h^{-1}) were calculated from the linear change

in CH_4 concentration as a function of time, chamber volume and temperature. Positive flux values indicated CH_4 uptake by the vegetation and negative values indicated a loss of CH_4 to the atmosphere.

4.6 Estimating annual C balance

In order to estimate the annual C balance for each sample plot, a number of non–linear multiple regression models were used (Wilson et al. 2007). The models were combined with a time series of PAR, vascular green area index (VGA), peat temperature (T_{5cm}) and water table position to calculate hourly P_G and R_{TOT}. Hourly NEE (P_G – R_{TOT}) was calculated and then integrated to provide an estimate of annual CO_2 balance (t CO_2 – C m^{-2} yr^{-1}) for each sample plot. Positive values indicated a net uptake of CO_2 from the atmosphere to the vegetation and negative values indicated a net loss of CO_2 to the atmosphere. Similarly, in order to reconstruct CH_4 fluxes, a number of non–linear multiple regression models were used (Wilson 2005). The models were combined with a time series of peat temperature (T_{10cm}) and water table position in order to calculate hourly CH_4 fluxes, which were then integrated to provide an estimate of annual CH_4 balance (t CH_4 – C m^{-2} yr^{-1}).

4.7 Results

CO$_2$ fluxes

Considerable seasonal and annual variation in CO_2 exchange (NEE) was observed at all microsites in this study (Fig. 4.4). All microsites were net sources of CO_2 in both years of the study and higher losses (with the exception of the soft rush/Yorkshire fog sample plots) were observed in 2003. In the summer months of both 2002 and 2003, NEE was positive in the cattail, canary grass and bog cotton/beaked sedge communities but was negative in the soft rush/Yorkshire fog sample plots.

Larger losses of CO_2–C were observed in the autumn / winter period of 2003 as a result of a much drier summer period that led to a considerable drop in water tables (Wilson et al. 2007). Deeper water tables have been shown to increase the aerobic zone at the surface of the peat body leading to higher losses of CO_2 due to increased heterotrophic respiration.

The annual CO_2–C balance (tonnes C ha^{-1} yr^{-1}) was negative for all microsites (i.e. loss of CO_2 from the peatland) and followed the trend; soft rush/Yorkshire fog > canary grass > cattail > bare peat > bog cotton/beaked sedge in 2002 and canary grass > soft rush/Yorkshire fog > cattail > bog cotton/beaked sedge > bare peat in 2003 (Table 4.1). There was considerable variation within each community, reflecting differences in plant biomass (VGA) and water table depths at each sample plot. In 2002, annual rainfall was 26.5% higher than the long-term average and helped maintain relatively high water tables for most of the year. In 2003 rainfall was 3.7% lower and resulted in a significant decrease in the water table throughout the cutaway.
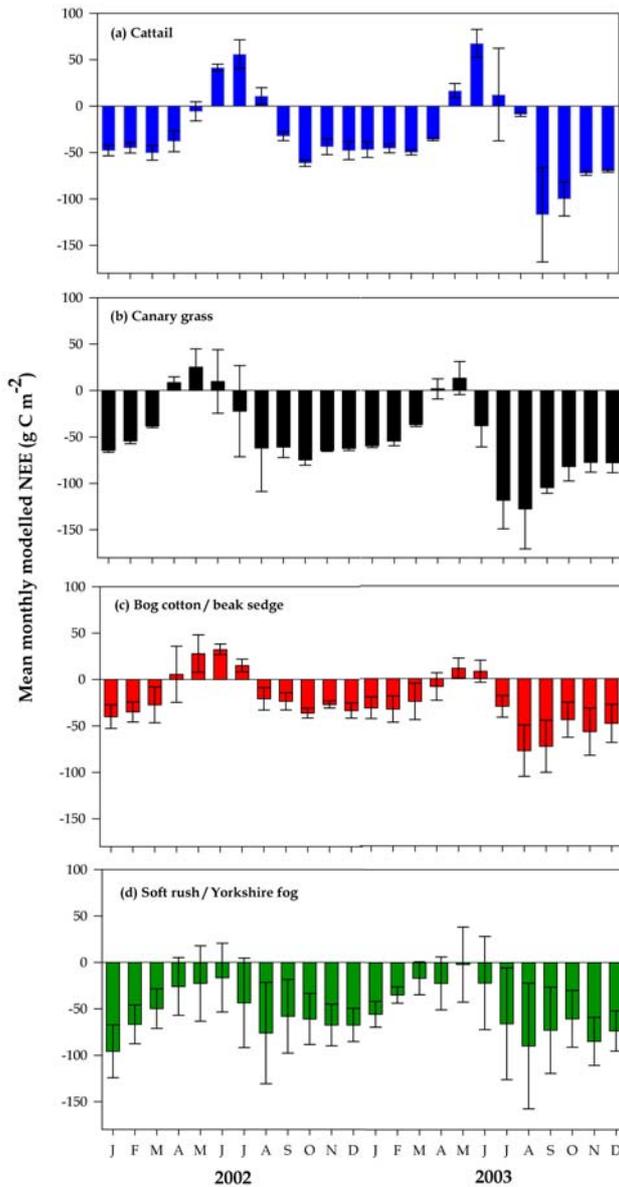
Fig. 4.4 Mean monthly reconstructed Net Ecosystem Exchange (NEE) (g CO_2–C m^{-2}) in (a) cattail (n = 2), (b) canary grass (n = 2), (c) bog cotton / beaked sedge (n = 4) and (d) soft rush / Yorkshire fog (n = 4) communities in 2002 and 2003. Positive values indicate net uptake of CO_2–C from the atmosphere to the vegetation. Negative values indicate a net loss of CO_2–C to the atmosphere.

CH_4 fluxes

CH_4 fluxes varied seasonally and inter-annually in the cattail, canary grass and bog cotton/beaked sedge microsites (Fig. 4.5). CH_4 emissions were highest in the summer periods as a result of a combination of optimal soil temperatures and increased supply of substrate to the methanogen microbial communities through root exudates and litter input. Wintertime emissions were higher in all microsites in 2002 as a result of higher water tables.
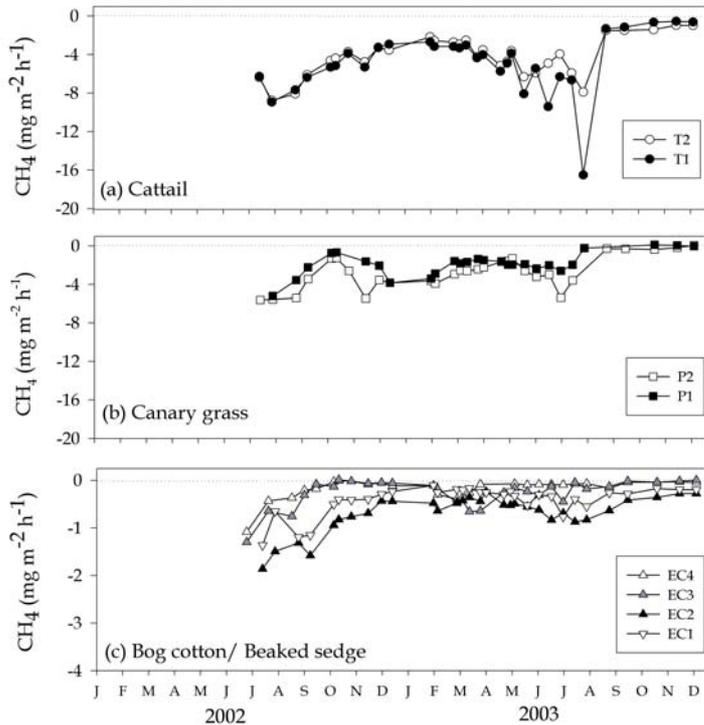
Fig. 4.5 Measured CH$_4$ fluxes (mg CH$_4$ m^{-2} h^{-1}) in (a) cattail (sample plots T1 and T2), (b) canary grass (P1 and P2) and(c) bog cotton / beaked sedge (EC1–EC4) from July 2002 to December 2003 at Turraun, Co. Offaly. Negative values indicate emission of CH$_4$ to the atmosphere. Positive values indicate an uptake of CH$_4$. Note differences in scale on y-axis.

Interannual variation in the CH$_4$-C balance (Table 4.1) was observed with higher emissions occurring in 2002. The cattail sample plots were the highest emitters of CH$_4$ releasing 0.29 ± 0.02 tonnes CH$_4$-C ha^{-1} yr^{-1} partly as a result of a pressurized internal gas transport system in that species that actively pumps oxygen to the deeper roots but also facilitates the emissions of CH$_4$. Emissions from the bog cotton/beaked sedge microsites were relatively low ranging from 0.2 ± 0.01 tonnes CH$_4$-C ha^{-1} yr^{-1} in 2003 to 0.03 ± 0.01 in 2002. No CH$_4$ fluxes were detected in the soft rush/Yorkshire fog and bare peat microsites as a consequence of site-specific characteristics i.e. a very deep water table position (soft rush/Yorkshire fog) and the absence of vegetation (bare peat).

Table 4.1 Mean reconstructed annual C balance (t CO_2-C and CH_4-C ha^{-1} yr^{-1}) at Turraun wetlands, Co. Offaly in 2002 and 2003. Negative values indicate a loss of C from the peatland to the atmosphere. Standard deviation shown in parentheses.

Microsite	2002			2003		
	CO_2-C	CH_4-C	Total	CO_2-C	CH_4-C	Total
Cattail	-2.64 (± 0.26)	-0.29 (± 0.02)	**-2.93** (± 0.24)	-4.94 (± 1.26)	-0.26 (± 0.02)	**-5.20** (± 1.24)
Canary grass	-4.59 (± 0.26)	-0.23 (± 0.02)	**-4.82** (± 0.24)	-7.54 (± 0.59)	-0.14 (±0.02)	**-7.68** (± 0.57)
Bog cotton/ beaked sedge	-1.61 (± 0.58)	-0.03 (± 0.01)	**-1.64** (± 0.59)	-4.05 (± 1.40)	-0.02 (±0.01)	**-4.07** (± 1.41)
Soft rush/ Yorkshire fog	-6.71 (± 2.90)	-	**-6.71** (± 2.90)	-6.37 (± 3.30)	-	**-6.37** (± 3.30)
Bare peat	-2.55 (± 0.35)	-	**-2.55** (± 0.35)	-3.08 (± 0.55)	-	**-3.08** (± 0.55)

5 Discussion

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Over the next few decades, large areas of peatlands that are currently being harvested will come out of production and become available for other uses. For future economic and environmental reasons, it is important that C gas exchange is quantified in these new ecosystems. The results from this study have shown that considerable differences exist between the land use options and require further discussion here.

(1) Commercial afforestation

The results of this study suggest that the Sitka spruce stand at Lullymore was a small C sink during 2000-2002. The rate of C uptake by the Sitka spruce stand is similar to the values of 8.6 t CO_2-C ha^{-1} yr^{-1} reported by Black et al. (2006) for a 15 year old Sitka spruce stand planted on a gley soil at Dooary, Co. Laois. The rate loss of soil C due to decomposition of root biomass, forest floor and the residual peat is higher than the range of values (2.75-4.79 t CO_2-C ha^{-1} yr^{-1}) found in afforested cutaway peatlands in southern Finland by Mäkiranta et al. (2007). Given that climatic conditions in Ireland are more favourable to organic matter decomposition, higher losses could be expected.

Lower rates of C losses have been reported for ombrotrophic peat soils (Hargreaves et al., 2003). Therefore, there is likely to be considerable variation between peat types in the magnitude of soil CO_2 emissions. The Lullymore site may be towards the upper end of the range. The residual peat in Lullymore is highly minerotrophic and, therefore, differences in peat type, pH and nutrient status may mean that the residual peat at the study site is more easily decomposable.

Some caution should be expressed when viewing the results for a number of reasons. Firstly, chronosequence studies elsewhere have indicated that there is a variation in the C sequestration capability (Black et al. 2006) and in soil CO_2 emissions (Zerva et al. 2005) over the lifetime of a stand. In the initial years following planting, the current annual increment (CAI) is likely to be low and the stand may be a net C source depending on the magnitude of soil CO_2 emissions. As the stand ages, CAI is likely to increase and the stand may represent a small C sink. The results from this study are, therefore, only pertinent for the stand and years in question. Secondly, the stand at Lullymore represents a relatively productive site and may not be representative of other stands growing on more ombrotrophic peat soils. Low nutrient availability combined with higher moisture content in the peat may result in considerably lower C sequestration rates in other

afforested cutaways. These same conditions may also result in lower soil CO_2 emissions.

(2) Natural regeneration

The birch/willow woodland at Turraun was estimated to be a C source during 2000-2002. As expected, the rate of C uptake is much lower than in the Sitka spruce stand at Lullymore. C sequestration was lower but close to the value reported by von Arnold et al. (2005) for a drained birch woodland in Sweden. As previously stated, the estimated rate of C uptake is highly uncertain, however it is likely that the site is a net C source. Managed stands of birch, either naturally regenerated or planted, may have greater potential for C uptake.

(3) Wetland creation

The results from this study suggest that the return of the C sink function in the wetlands at Turraun is unlikely to occur under the climatic and hydrological conditions observed. The importance of maintaining high water table levels, especially during the summer period have been stressed in other studies (Richert et al. 2000; Chimmer and Cooper 2003a). Appropriate water management can help reduce the CO_2 source potential of cutaway peatlands (Waddington et al. 2002). In contrast to pristine peatlands, cutaways are less able to maintain a water table close to the surface. Keeping the water table at levels sufficiently high to minimise aerobic decomposition and CO_2 loss is difficult due to the absence of an acrotelm, which stabilises the water table (Waddington and Price 2000), structural changes in the residual peat brought about by drainage (Price et al. 2003) and high evaporative losses. During periods when evapotranspiration losses are greater than precipitation, this can result in a large and rapid drop in the water table position that produces an increased aerobic zone and subsequently higher losses of CO_2. However, under the same circumstances CH_4 emissions are likely to be much reduced. The use of mulches has been proposed as a means of reducing evaporative losses from the peat during *Sphagnum* recolonisation. However, Waddington et al. (2003) have observed that decomposition of the mulch in turn adds to the overall losses of CO_2 from the peatland.

The annual losses of C from the bare peat microsites in this study were in most cases lower than in the vegetated microsites. Of course, this poses the question; why allow the cutaway to undergo revegetation at all? Indeed, taken in isolation, the results from this two-year study would suggest that the return of vegetation has a negative effect on the C status of the cutaway. However, recolonisation by vegetation is recognised as an essential first step on the road to *long term* C accumulation, insofar as it brings back the C fixation component i.e. photosynthesis. When combined with appropriate water management, recolonisation can result in the return of suitable peatland species (Farrell and Doyle 2003). For example, Tuittila et al. (2000) observed that raising the water table above or close to the soil surface promoted a rapid development of minerotrophic vegetation. The combination of rewetting and increased vegetation

coverage resulted in the return of the C sink function in two years. Interestingly, in this study the lowest losses of C in the vegetated microsites were observed in the plant species most characteristic of pristine fens i.e. bog cotton and beaked sedge.

The considerable losses of C observed at Turraun wetlands are higher than those reported elsewhere due in large part to high wintertime losses of CO_2. However, it is difficult to put these values in perspective, as there have been no other C gas studies undertaken in rewetted peatlands in Ireland. Although the return of peat formation and C accumulation may be unlikely in the short-term, re-establishment of vegetation coupled with suitable hydrological management may reduce the magnitude of C gas losses from the peatland in the future. On the basis of this study alone, restoration of the C sink function in temperate maritime climatic zones will present a considerable challenge in the years ahead. Further research is desirable to determine whether the results shown here for Turraun can be extrapolated to other rewetted cutaways not only in Ireland but also in the temperate, maritime climatic zone.

Methane (CH_4) values were not measured in either the Sitka spruce or naturally regenerated stands. Results from other studies suggest that a lowering of water table through the installation of drainage ditches will result in zero CH_4 emissions as a consequence of a deeper oxic layer or in a small CH_4 uptake. However, some emissions may still occur if the drainage ditches are not maintained. As CH_4 is a more powerful GHG than CO_2, the effect of even low emissions can have a major impact on the Global Warming Potential (GWP) of an ecosystem. In Fig. 5.1, the GWP of the CARBAL study sites and a pristine blanket bog in Kerry are compared over a 100-year time horizon. With the exception of the Sitka spruce stand, all the land uses have a warming effect on the global climate. This is primarily due to the contribution of CH_4 to the GWP balance. Although not quantified in this study, nitrous oxide (N_2O) fluxes could also have a major effect on the GWP balance.
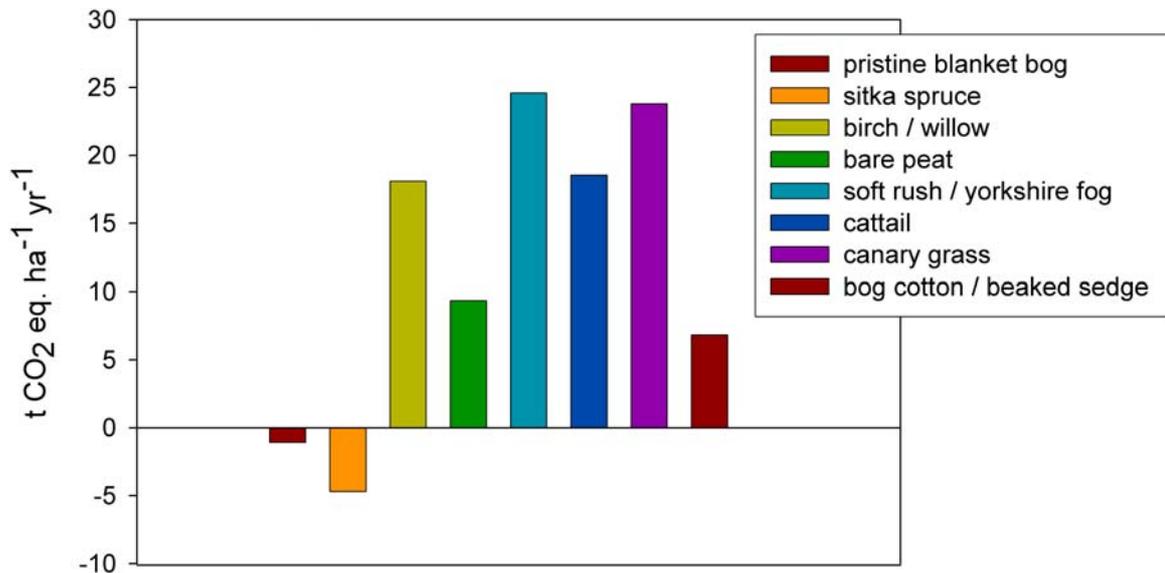
Fig. 5.1. Global warming potential (t CO_2 equivalents ha^{-1} yr^{-1}) for the CARBAL land use options in 2002. CH_4 emissions were converted into CO_2 equivalents by assuming a GWP of 23 over a 100-year horizon (IPCC 2001). For comparison purposes, values for a pristine blanket bog (Laine 2006) are shown. Positive values indicate a net warming effect on the climate and negative values indicate a cooling effect.

From the results of this study, it is clear that ranges of management options are required in order to both minimise losses of C from the cutaway and maximise uptake.

1. Prior to the cessation of peat harvesting, a clear coherent afteruse plan with regard to C should be in place for each cutaway peatland.

2. For wetland creation, it is essential that the water table be maintained close to the surface throughout the year in order to minimise persistent losses of CO_2 from both the bare peat surfaces and vegetation communities. As aerobic decomposition occurs up to 10,000 times faster than anaerobic decomposition, a high water table will have the dual effect of reducing CO_2 emissions and will also promote recolonisation by appropriate wetland vegetation and, over time, may lead to the return of the CO_2 sink function. However, high water tables combined with the return of wetland vegetation may also result in increased CH_4 emissions. The long-term objective for wetland creation, in regard to the annual C balance, is to reach a point where the losses of CH_4 are offset by CO_2 uptake.

3. Management of the naturally regenerated woodlands may result in higher rates of C uptake than in unmanaged stands.

Concluding remarks

Of the land use options examined, forestry appears to be the most promising. The stand studied, at Lullymore, has long been considered atypical and to that extent, the results obtained may be unrepresentative. It was selected because, at the time, it was one of the very few, perhaps the *only* pole-stage stand of spruce on milled cutaway. It should be borne in mind, however, that the species, Sitka spruce, is not recommended for extensive industrial cutaway afforestation; Norway spruce (*Picea abies* L.) is preferred because of its greater tolerance to spring frost (Renou et al. 2007). Norway spruce is a slower growing species than Sitka and is, therefore, unlikely to achieve the same level of productivity. As such, the C sequestration potential will be correspondingly less. While this would suggest a smaller sink potential, it should be borne in mind that emissions of CO_2 from this site were remarkably high, considerably greater than anticipated. Clearly, further work is needed on a range of cutaway forest sites. While no sites are available of a stage of forest development similar to Lullymore, it is likely that some less productive stands of similar age can be identified for future study. It is clearly impossible to predict the outcome of such studies, but the evidence gathered to date suggests that afforested peatlands may prove to be a modest C sink. However, this applies only to fast growing coniferous stands. Our results suggest that unmanaged feral birch sites are always likely to be a greenhouse gas source.

The potential of coniferous forests to sequester C has to be seen in the overall context of cutaway afteruse. Only a proportion of the total cutaway peatland area will ever be suitable for commercial forestry. This has been estimated by Bord na Móna to be between 16,000 and 20,000 ha. The remainder, 75% or more, of the cutaway area is likely to consist of artificial lakes, wetland communities and scrub woodland. It is questionable whether any of these terrestrial alternatives, will have a greenhouse sink potential.

Acknowledgements

Appendix 1. Publications

<u>Peer reviewed journals</u>

Green C., Tobin B., O'Shea M., Farrell E. P. and Byrne K. A. 2005. Above- and belowground biomass measurements in an unthinned stand of Sitka Spruce (*Picea sitchensis* (Bong) Carr.). European Journal of Forest Research doi. 10.1007/s10342-005-0093-3

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Wilson D., Tuittila E.-S., Alm J., Laine J., Farrell E. P. and Byrne K. A. 2007 Carbon dioxide dynamics of a restored maritime peatland. Écoscience. 14. 1. 71-80

<u>Abstracts and conferences</u>

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Thesis

Wilson D.2005. Carbon dioxide, methane and vegetation dynamics in a rewetted industrial cutaway peatland. PhD thesis. School of Biology and Environmental Science. University College Dublin.

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