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Carbon Restore –
The Potential of Restored Irish Peatlands for Carbon Uptake and Storage
Environmental Protection Agency

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Carbon Restore – The Potential of Restored Irish Peatlands for Carbon Uptake and Storage

The Potential of Peatlands for Carbon Sequestration

(2007-CCRP-1.6)

CCRP Report

Prepared for the Environmental Protection Agency

by

University College Dublin

Authors:

David Wilson,1 Florence Renou-Wilson,1 Catherine Farrell,2 Craig Bullock3 and Christoph Müller1

1 School of Biology and Environmental Science, University College Dublin,
2 Bord na Móna, 3 School of Geography, Planning and Environmental Policy

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

Telephone: +353 53 916 0600 Fax: +353 53 916 0699
Email: info@epa.ie Website: www.epa.ie
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The EPA CCRP Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

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Details of Project Partners

Professor Christoph Müller
University College Dublin School of Biology and Environmental Resource
Agriculture & Food Science Centre
University College Dublin
Belfield
Dublin 4
Ireland
Tel.: +353-01-716-7781
Email: christoph.mueller@ucd.ie
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Executive Summary

Industrial cutaway peatlands are highly degraded ecosystems that release significant quantities of carbon dioxide (CO$_2$) to the atmosphere annually. Their restoration offers the potential to reduce CO$_2$ emissions and to re-establish the carbon (C) sink function characteristic of natural peatlands. In this study, CO$_2$, methane (CH$_4$) and nitrous oxide (N$_2$O) fluxes were quantified over a 12-month period (1 January to 31 December 2009) at a rewetted industrial cutaway peatland at Bellacorick, Co. Mayo.

The site was restored in 2003, and this has resulted in a persistently high water table level throughout the study site and the extensive recolonisation of the former bare peat substrate by a range of vascular and moss vegetation. These include: (i) soft-rush-Sphagnum moss-dominated communities, (ii) Sphagnum moss-dominated communities, (iii) bog cotton-dominated communities, (iv) bare peat and (v) open water.

For the period of the study, the vegetated communities were net annual CO$_2$-C sinks, sequestering an average 279±246g C m$^{-2}$ yr$^{-1}$. Conversely, they were also significant net annual CH$_4$-C sources of 10.1±3.6g C m$^{-2}$ yr$^{-1}$. The bare-peat and open-water areas were net CO$_2$-C sources, releasing 40 and 53g C m$^{-2}$yr$^{-1}$ respectively to the atmosphere. N$_2$O emissions were negligible throughout the study period. Calculation of the global warming potential (GWP, 100-year horizon) showed that the soft-rush-Sphagnum and bog cotton communities were net GHG sinks (i.e. causing a potential cooling effect on the climate). In contrast, the Sphagnum moss-bog cotton communities, bare-peat and open-water areas were net GHG sources (i.e. causing a potential net warming impact on the climate).

The current project assessed the potential economic value of restoration in terms of avoided losses and gains of C (€/tonne CO$_2$-eq ha$^{-1}$) through the use of a number of timeline scenarios. These followed the peatland from the cessation of peat extraction ($T_{zero}$), through rewetting ($T_{r}$) and on to the present day ($T_{present}$). The results show that in the period $T_{1}$ to $T_{present}$, an estimated 75 tonnes CO$_2$-eq ha$^{-1}$ was mitigated by the restoration actions at Bellacorick – resulting in an estimated value of €1506 ha$^{-1}$ in avoided losses. In addition, net C sequestration at the peatland during the 12-month period of this study ($T_{present}$) was worth an estimated €118 ha$^{-1}$ yr$^{-1}$.

The results from this study indicate that restoration at Bellacorick has been successful with regard to re-establishing the C sink function. This observation highlights the potential use of restored industrial cutaway peatlands for C offsetting. However, there are a number of caveats. Firstly, studies elsewhere have shown that inter-annual variation in GHG fluxes is a characteristic feature of peatlands in general. As such, care should be taken in interpreting the results presented in this report as they represent a single 12-month period only. Secondly, the ongoing dynamic changes in vegetation composition observed at the study site may lead to a similar level of change in GHG fluxes in the future. Thirdly, while the results from this study indicate that some aspects of ecological functioning have been restored at Bellacorick, it may not be possible to recreate conditions to the same extent in other degraded peatlands.

Given that 30,000ha of industrial cutaways may be available for restoration/wetland creation over the next 20 years, it is critical that appropriate GHG management plans are in place prior to the cessation of peat extraction. The plans should include a detailed assessment of the physical and nutrient characteristics of each cutaway site and should seek to identify the best approach for the avoidance of GHG emissions in the first instance (e.g. drain blocking, shallow inundation, etc.). The plans should also identify the potential of each cutaway site in regard to C sequestration in the medium/long term, and highlight the criteria required to achieve those objectives.
1 Introduction

1.1 Background

The most recent assessment report from the Intergovernmental Panel for Climate Change (IPCC) stated that ‘most of the observed increase in global average temperatures since the mid-twentieth century is very likely due to the observed increase in anthropogenic greenhouse gas (GHGs) concentrations’ (IPCC 2007, authors’ emphasis). The atmospheric concentration of the GHGs – carbon dioxide (CO$_2$), methane (CH$_4$) and nitrous oxide (N$_2$O) – has increased from their pre-industrial values by 35, 148 and 18% respectively. This is primarily a result of human activities – such as fossil-fuel burning, land-use change and agriculture (IPCC 2007). Climate models predict that at the current rate of GHG emissions a significant increase in the global average temperature can be expected over the next century, concomitant with reduced snow and ice cover, sea-level rises and an increase in extreme weather events (IPCC 2007).

Peatlands play a major role in the global carbon (C) cycle and subsequent regulation and maintenance of the global climate (Vasander and Kettunen 2006, Dise 2009). There is an estimated 270 to 455 billion tonnes of C stored in boreal and sub-arctic peatlands (Sjörs 1980, Gorham 1991, Turunen et al. 2002), and a further 83 billion tonnes may be stored within tropical peatlands (Rieley et al. 2008). The ability of peatlands to continue to actively remove and store atmospheric C and thereby act as a buffer to climate change is highly dependent on the degradation status of the individual peatland.

Damaged peatlands are a significant source of CO$_2$ to the atmosphere (Page et al. 2002, Waddington et al. 2002, Wilson 2008, Joosten 2009) and the restoration of damaged peatland ecosystems has been suggested as one of the most cost-effective ways of reducing GHG emissions and mitigating the effects of climate change (Parish et al. 2008, Motherway and Walker 2009). Over 80% of Irish peatlands have been damaged to some extent (Renou-Wilson et al. 2011). These range from peatlands that have undergone relatively minor damage, and where some of the ecosystem functioning remains relatively intact (e.g. low-impact traditional hand-cut peat extraction in some blanket bogs) to peatlands that have undergone extreme damage and where much of ecosystem functioning has been destroyed (e.g. industrial cutaway peatlands). In the latter category, restoration of the main ecosystem functions, in particular the ability to actively sequester and store C, presents a major challenge. While the rewetting of the industrial peatland and subsequent recolonisation by desirable plant species have been shown to lead to a reduction in CO$_2$ emissions (Waddington and Warner 2001, Drösler 2005) and a return to C sequestration in other countries (Tuittila et al. 1999), knowledge in Ireland as to how such remedial management actions may affect C gas exchange in these highly degraded peatlands is limited.

Currently, Annex 1 Parties to the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol are obliged to prepare annual National Inventory Reports (NIR), detailing GHG emissions and removals from six different sectors: (i) energy, (ii) industrial processes, (iii) solvents and other product use, (iv) agriculture, (v) land use, land use change and forestry (LULUCF) and (vi) waste. Greenhouse gas fluxes from natural peatlands are not reported because the fluxes are not anthropogenic in origin (O’Brien 2007). Emissions associated with peat combustion are recognised and are reported under the energy sector with emissions from industrial peatlands reported under LULUCF (Wetlands: Category 5.D). Although the rewetting of drained peatlands as a climate-mitigation action has been addressed in the UNFCCC and IPCC, it has not yet led to clear implementation rules or obligations. Because of the lack of scientific data, no good-practice guidance has been given for assessing GHG fluxes on rewetted organic soils (IPCC 2006, O’Brien 2007). However, in June 2010, the Subsidiary Body for Scientific and Technological Advice (SBSTA, i.e. the body that provides technical advice to the UNFCCC), took a decision to ‘clarify, improve and update information’ in regard to methodologies to
account for information gaps from wetland uses not currently covered. These include drained wetlands, the rewetting of previously drained wetlands and the restoration of wetlands (SBSTA 2010). This decision suggests an acknowledgement that emissions from drained wetlands are significant and that rewetting peatlands is an important contribution to decreasing GHG emissions. At the UNFCCC meeting in Cancún (December 2010), unanimity was reached among LULUCF negotiators on the definition and content of a new activity under the Kyoto Protocol, called ‘rewetting and drainage’. The definition of the proposed new activity is:

Rewetting and drainage is a system of practices for rewetting and draining on land with organic soil that covers a minimum area of 1 ha. The activity applies to all lands that have been drained and/or rewetted since 1990 and that are not accounted for under any other activity as defined in this appendix, where drainage is the direct human-induced lowering of the soil water table and rewetting is the direct human-induced partial or total reversal of drainage.

(Document: FCCC/KP/AWG/2010/CRP.4/Rev.4)

Furthermore, the utilisation of rewetted peatlands in voluntary C offset projects has recently been made possible by the Verified Carbon Standard Program (VCS) in the Peatland Rewetting and Conservation module (PRC) of its new Agriculture, Forestry and Other Land Uses (AFOLU) Guidelines (8 March, 2011). Implicit within these objectives is that both the avoided GHG losses and C sequestered by the new rewetted ecosystems are ‘measureable, reportable and verifiable’ (Joosten and Couwenberg 2009). Therefore, it is essential that the potential of these new ecosystems to (i) avoid GHG emissions and (ii) sequester C is assessed and quantified properly in light of possible accounting changes in the post Kyoto Protocol commitment period (2012 onwards) and in view of possible inclusion in C offset projects.

1.2 Literature Review

Box 1.1. Note on terms used in this report

CO₂-C represents the carbon atom contained within the CO₂ molecule. In terms of the overall molecular weight of CO₂, the carbon atom accounts for 12/44 or 27%. Thus, a multiplier of 3.667 is required in order to convert CO₂-C values to CO₂.

CH₄-C represents the carbon atom contained within the CH₄ molecule. In terms of the overall molecular weight of CH₄, the carbon atom accounts for 12/16 or 75%. Thus, a multiplier of 1.334 is required in order to convert CH₄-C values to CH₄.

N₂O-N represents the nitrogen atoms contained within the N₂O molecule. In terms of the overall molecular weight of N₂O, the nitrogen atoms accounts for 28/44 or 64%. Thus, a multiplier of 1.571 is required in order to convert N₂O-N values to N₂O.

Negative gas flux values indicate an uptake by the peatland and positive gas flux values indicate a loss from the peatland to the atmosphere.

1.2.1 Greenhouse Gas Exchange in Natural Peatlands

Natural peatlands, that are peatlands that are intact and undamaged, are able to act as long-term C sinks, primarily as a result of a persistently high water table (WT) within the peat (Belyea and Clymo 2001, Mäkilä et al. 2001, Belyea and Malmer 2004, Lund et al. 2010), which creates conditions whereby the amount of CO₂ fixed by the peatland vegetation during photosynthesis (Pₚ) is greater than that released during ecosystem respiration (Rₑₑ). NEE has a strong diurnal and seasonal variation (Nieveen et al. 1998, Lafleur et al. 2001, Vasander and Kettunen 2006), with the highest values during daytime in the summer months (Wilson et al. 2007a). However, numerous studies have reported strong inter-annual variations in NEE (Shurpali et al. 1995, Roulet et al. 2007, Worrall et al. 2009a, Koehler et al. 2010, Sottocornola and Kiely 2010), and a peatland can switch easily from being an annual CO₂
sink to an annual CO₂ source in consecutive years (Shurpali et al. 1995), although over the medium to long term, as evidenced by the accumulated peat, they are net C sequesters. The magnitude of the C sink/source function is determined to a large extent by ecosystem respiration (Charman 2002). Composed of two respiratory processes – autotrophic (plant) and heterotrophic (microbial) – ecosystem respiration has been shown to be very sensitive to changes in both soil temperature (Lafleur et al. 2005, Laine et al. 2006, Wilson 2008) and fluctuations in the WT (Laine et al. 2007a, Riutta et al. 2007b). When the WT level is at or close to the surface of the peatland, decomposition of organic matter (plant litter and root exudates) within the peat profile is constrained by the absence of oxygen and so CO₂ production is relatively small. When the WT drops (either through drought or damage to the peatland), the magnitude of the soil CO₂ component increases significantly as a consequence of higher rates of decomposition of the peat (Silvola et al. 1996, Alm et al. 1999, Wilson 2008).

While CO₂ is the largest component of the peatland C balance, CH₄ fluxes are also significant. Natural peatlands are a major source of atmospheric CH₄ (Bubier et al. 1993, Nykänen et al. 1998, Vasander and Kettunen 2006, Laine et al. 2007b) releasing an estimated 20–65 Terragrams (Tg) CH₄ yr⁻¹ (Matthews and Fung 1987, Cao et al. 1998, Walter et al. 2001, Mikaloff Fletcher et al. 2004), which equates to approximately 4–11% of the total atmospheric burden of around 582 Tg CH₄ yr⁻¹ (IPCC 2007). CH₄ fluxes have

![Diagram of C balance](image)

**Figure 1.1** The carbon balance of a natural Atlantic blanket bog at Co. Kerry, Ireland. Values adapted from Koehler et al. (2010). Negative values indicate a net uptake of C by the peatland and positive values indicate a net loss of C to the atmosphere.
been shown to be highly correlated to the position of the WT, with higher emissions recorded when the WT is close to the surface of the soil (Roulet et al. 1992, Nykänen et al. 1998, Bubier et al. 2005, Laine et al. 2007b, Couwenberg et al. 2011). CH₄ fluxes are also strongly influenced by the vegetation composition of the peatland, in particular aerenchymatic plant species, such as sedges (Joabsson et al. 1999, Ström et al. 2003, Strack et al. 2006). Because of their unique cellular structure, these plant species facilitate the movement of CH₄ from the anoxic peat directly to the atmosphere, bypassing the oxic peat zone where CH₄ is oxidised to CO₂. Losses of dissolved organic carbon (DOC) and particulate organic carbon (POC) from the peatland in run-off to adjacent water courses have been shown to be considerable (Fig. 1.1, Worrall et al. 2003, Worrall and Burt 2005, Roulet et al. 2007, Jager et al. 2009, Koehler et al. 2009, Worrall et al. 2009a) and may be accentuated by future climate warming (Freeman et al. 2001). Studies have shown that fluxes of N₂O from natural peatlands are generally negligible (Martikainen et al. 1995, Nykänen et al. 1996), although significant N₂O emissions have been reported during periods of drought and during the subsequent rise in WT levels within the peatland (Goldberg et al. 2010).

1.2.2 Industrial Peat Extraction

Connolly and Holden (2009) have estimated that peat soils currently cover around 20% of the land area in the Republic of Ireland, although only a small percentage of this area is in a natural or intact condition (Douglas et al. 2008). In over 80% of the peatland area, the main ecosystem functions characteristic of intact natural peatlands (hydrology, vegetation dynamics, C cycling etc.) have been seriously impaired as a consequence of land-use changes, for example agricultural reclamation, forestry and peat extraction (Renou-Wilson et al. 2011).

In recent times, the majority of peat has been extracted using either small-scale mechanisation (e.g. tractor mounted hoppers) or more large-scale industrial processes (milled peat methods). Since 1949, most of the peat has been extracted industrially by the semi-state body Bord na Móna, which currently removes around 4 million tonnes of peat per year (http://www.bnm.ie). Around 3 million tonnes of the extracted peat is burned in the peat-fired power stations at Lough Ree, West Offaly and Edenderry, or made into peat briquettes for use in the residential sector. The remainder of the peat (around 1 million tonnes) is utilised in horticultural products.

Industrial peat extraction has a number of fundamental impacts on peatland ecosystem functioning. In order to facilitate the use of heavy machinery on the peatland during the peat-extraction process, drainage ditches are installed at 15m intervals. This results in a lowering of the WT and leads to increased oxidation of the peat substrate, and a rise in soil CO₂ emissions (Holmgren et al. 2006). Subsequent removal of the vegetation and upper fibrous layers of peat removes the CO₂ fixing capacity (i.e. photosynthesis) of the peatland (Waddington and Price 2000) and the ecosystem is transformed from an annual CO₂ sink and CH₄ source (natural peatland) to a large CO₂ source and reduced CH₄ source (Table 1.1), although CH₄ emissions from drainage ditches may still be very significant (Nykänen et al. 1996, Sundh et al. 2000, Waddington et al. 2009). N₂O emissions, considered negligible in natural peatlands, may increase significantly following drainage (Martikainen et al. 1995, Augustin et al. 1998), particularly in nutrient-rich peatlands (Kasimir-Klemedtsson et al. 1997, Schils et al. 2008).

In Ireland, industrial peat extraction typically removes around 15–22.5cm of peat per year (http://www.bnm.ie) and continues until either (i) the underlying mineral substrate is reached, (ii) fossilised trees are encountered within the peat profile or (iii) it proves to be uneconomic to pump the drainage water out of the peatland (Farrell and Doyle 2003). Following the cessation of industrial peat extraction, the peatland is designated a ‘cutaway’ and is potentially available for other uses (Table 1.2). In Ireland, these uses have included agriculture and commercial forestry (now limited), and natural re-generation of wetlands (open water, fen, reedbed and acidic wetlands) and woodland (birch and willow scrub) habitats. Studies have shown that GHG dynamics vary considerably across the various land-use options. For example, Byrne et al. (2007a) observed that an afforested cutaway was a C sink of 1.25t CO₂-C ha⁻¹ yr⁻¹ (4.57 t CO₂eq. ha⁻¹ yr⁻¹) but that a naturally regenerated cutaway dominated by birch and willow was a large C source of 5.25t CO₂-C ha⁻¹ yr⁻¹ (19.22 t CO₂eq. ha⁻¹ yr⁻¹) (Byrne et al. 2007b). Similarly, the costs associated with development of these new land uses vary considerably (Table 1.2). Relatively low costs are attached to
Table 1.1. Greenhouse gas fluxes (CO$_2$-C, CH$_4$-C and N$_2$O-N; tonnes ha$^{-1}$ yr$^{-1}$) from peat-extraction areas (non-vegetated bare peat). Positive values indicate a flux from the peatland to the atmosphere.

<table>
<thead>
<tr>
<th>Location</th>
<th>CO$_2$-C Tonnes ha$^{-1}$ yr$^{-1}$</th>
<th>CH$_4$-C Tonnes ha$^{-1}$ yr$^{-1}$</th>
<th>N$_2$O-N Tonnes ha$^{-1}$ yr$^{-1}$</th>
<th>Reference source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finland</td>
<td>2.40</td>
<td>0.002</td>
<td>0.0002</td>
<td>Nykänen et al. 1996</td>
</tr>
<tr>
<td>Sweden</td>
<td>0.55–2.73</td>
<td>0.003–0.034*</td>
<td>–</td>
<td>Sundh et al. 2000</td>
</tr>
<tr>
<td>Canada</td>
<td>3.98h</td>
<td>–</td>
<td>–</td>
<td>Waddington and Warner 2001</td>
</tr>
<tr>
<td>Canada</td>
<td>0.88–3.97h</td>
<td>–</td>
<td>–</td>
<td>Waddington et al. 2002</td>
</tr>
<tr>
<td>Canada</td>
<td>3.02</td>
<td>0.014</td>
<td>–</td>
<td>Cleary et al. 2005</td>
</tr>
<tr>
<td>Sweden</td>
<td>2.73c</td>
<td>0–0.02</td>
<td>0–0.016</td>
<td>Holmgren et al. 2006</td>
</tr>
<tr>
<td>Finland</td>
<td>3.16</td>
<td>0.004</td>
<td>0</td>
<td>Holmgren et al. 2006</td>
</tr>
<tr>
<td>Ireland</td>
<td>1.9–3.5</td>
<td>-0.001</td>
<td>–</td>
<td>Wilson et al. 2007</td>
</tr>
<tr>
<td>Finland</td>
<td>1.89–11.18</td>
<td>0.054</td>
<td>0.002</td>
<td>Alm et al. 2007a</td>
</tr>
<tr>
<td>IPCC d</td>
<td>0.2–1.1</td>
<td>0</td>
<td>0.001–0.002</td>
<td>Penman et al. 2003</td>
</tr>
</tbody>
</table>


a Includes emissions from drainage ditches, b May–August period only, c Includes emissions from stockpiles, d IPCC default emission factor for nutrient poor and nutrient rich industrial peatlands (CO$_2$-C and N$_2$O-N) and for drained organic soils (CH$_4$-C).

Table 1.2. Future dominant land-use/habitats on Bord na Móna cutaway bogs (post-peat production) based on current estimates and evidence of vegetation succession patterns and estimated cost of establishment.

<table>
<thead>
<tr>
<th>Land use</th>
<th>Present areas$^\S$ (ha)</th>
<th>Future areas$^\S$ (ha)</th>
<th>Cost ($€ ha^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Afforestation</td>
<td>4,000</td>
<td>5–10,000</td>
<td>3,200*</td>
</tr>
<tr>
<td>Birch woodland (scrub)</td>
<td>4,000</td>
<td>20,000</td>
<td>120</td>
</tr>
<tr>
<td>Alkaline wetland</td>
<td>5,000</td>
<td>20,000</td>
<td>250</td>
</tr>
<tr>
<td>Acid wetland</td>
<td>6,500</td>
<td>20,000</td>
<td>400</td>
</tr>
</tbody>
</table>

$^\S$ Bord na Móna internal reports, * Cost covered by grant assistance.

Birch woodland as the ecosystem usually develops spontaneously with minimal human impact. The cost of wetland creation is somewhat higher as mechanical diggers/bulldozers are used to block drainage ditches and landscape the peatland. The largest costs are associated with afforestation of the cutaway peatland (cultivation, fencing, planting, weed control etc.) but grant subsidies are available. The costs associated with restoration of afforested peatlands are generally higher ($€2,194 to €4,378 ha$^{-1}$; Coillte EU LIFE project), and the cost of rehabilitating peatlands damaged by domestic turf extraction is likely to be substantial given that the peatland may have to be purchased from the landowner in the first place.
1.2.3 Restoration of Industrial Cutaway Peatlands

The term *restoration* is often associated with efforts to return a damaged ecosystem to the state that existed immediately prior to the degrading action. In the case of industrial cutaway peatlands in Ireland, this is clearly impossible as (a) a large volume of peat has been extracted industrially and (b) the peat remaining following the cessation of peat extraction is unsuitable for supporting the vegetation communities characteristic of climax peatland ecosystems (Wheeler and Shaw 1995, Farrell and Doyle 2003). However, restoration can also imply that the objective is to return the ecosystem to some point along its original developmental trajectory, which was curtailed when peat extraction began (Vasander et al. 2003). In this regard, the ‘re-establishment of the self-regulatory mechanisms necessary to sustain peat growth without further human interventions’ (Quinty and Rochefort 2003) is an obvious goal. Restoration of cutaway peatlands presents considerable difficulties. Initial vegetation colonisation of the peat substrate following the cessation of peat extraction can be a slow process (Salonen et al. 1992, Quinty and Rochefort 2003) primarily as a result of the absence of typical peatland plant species on the surface (Curran and MacNaeidhe 1986) and in the seed bank (Huopalaainen et al. 1998), and the distance of residual plant populations from the cutaway (Campbell et al. 2003). Plant establishment and survival are made more difficult by the conditions that may exist in the upper layers of the peat body. These conditions typically include unsuitable nutrient status (Wind-Mulder et al. 1996), instability of the peat surface (Campbell et al. 2002), WT fluctuations (Price 1997), evaporative losses (Waddington and Price 2000, Van Seters and Price 2001) and high peat temperatures in mid-summer, which can be more of a challenge in climatic regions with more extreme weather events than Ireland.

Active management methods are employed to create the conditions that will allow the restoration process to develop (Quinty and Rochefort 2003). This approach generally involves two components. Firstly, the WT is raised by blocking the drainage ditches and creating a bund or ridge to retain the water within the peatland (Wheeler and Shaw 1995). These measures are necessary to create suitable conditions (e.g. a persistently high WT) for the establishment of desirable peatland vegetation communities (Charman 2002) and can have an immediate effect in areas where vegetation is already established (Farrell and Doyle 2003). For example, Tuittila et al. (1999) reported a significant increase in the cover of *Eriophorum vaginatum* following the blocking of drainage ditches in an abandoned cutaway peatland in southern Finland. Similarly, Tuittila et al. (2000b) noted a rapid succession towards a closed mire vegetation when the WT was raised close to or above the soil surface. The second component involves the re-introduction of species that are characteristic of natural peatlands (Cooper and MacDonald 2000), in particular, peat-forming species such as Sphagna (Rochefort et al. 2002, Tuittila et al. 2003). ‘Donor’ peatlands have been used widely in Canada, whereby Sphagna are harvested from a nearby natural peatland and then spread on the damaged peatland. Re-establishment has been shown to be enhanced by the use of companion species, such as *Polytrichum commune* (Groeneveld et al. 2007) and *Eriophorum angustifolium* (Ferland and Rochefort 1997), by peat-surface topography manipulations that create a series of ridges and shallow basins that enhance conditions for *Sphagnum* establishment (Ferland and Rochefort 1997, Farrell and Doyle 2003, Campeau et al. 2004) and by fertilisation (Sottocornola et al. 2007). Farrell (2001) noted a rapid spread and establishment of *Sphagnum* species on industrial cutaway bog in Mayo following simple rewetting measures, with typical peatland species, such as *Sphagnum* mosses and sedges, such as *Eriophorum angustifolium*, establishing within relatively short timeframes (three to ten years).

In Ireland, a considerable amount of research on restoration and management of peatlands has been carried out over the last number of decades (e.g. Egan 1998, O’Connell 1998, Schouten 1998, Foss et al. 2001, Schouten 2002, Farrell and Doyle 2003, Delaney 2008, Malone and O’Connell 2009). This research has, in turn, been actively implemented at the peatland site level by governmental agencies, such as the National Parks and Wildlife Service (NPWS), non-governmental organisations, such as the Irish Peatland Conservation Council, semi-state bodies such as Coillte and Bord na Móna, and by private individuals. Restoration of damaged peatlands is very site specific and strongly influenced by a number of factors – for example, peatland type, the degradation status of the peatland (Farrell 2008) and topography (Wheeler and Shaw 1995). To date, around 11,000ha of acid and
alkaline wetlands have been created by Bord na Móna. As the post-industrial use of the cutaway is largely determined by the residual peat type, underlying soil type and drainage conditions (Renou et al. 2006), a further 30,000ha of cutaway peatland could be suitable for restoration/rehabilitation to wetlands over the next decades.

1.2.4 Greenhouse Gas Exchange in Restored Peatlands

Various studies have reported a reduction in the magnitude of CO₂ losses when the peatland was rewetted and vegetation became re-established (Waddington and Price 2000, Waddington and Warner 2001, Drösler 2005). Other studies have reported C gas dynamics similar to those of natural peatlands (i.e. CO₂ sink and CH₄ source) within a short time frame following active rewetting and recolonisation (Komulainen et al. 1998, Komulainen et al. 1999, Tuittila et al. 1999, Soini et al. 2009) or from spontaneous regeneration of the peatland (Bortoluzzi et al. 2006). In the period following rewetting, peat oxidation rates are low as a consequence of the anoxic soil conditions and most of the C sequestered is contained within the peatland biomass pool (leaves, stems, roots). Over longer time frames some studies have reported a decrease in the amount of CO₂ sequestered annually (Yli-Petäys et al. 2007). As the peatland biomass pool increases over time, it will eventually approach a steady-state C sequestration saturation point (Anderson et al. 2008). The accumulation of organic matter (and the C therein) in a new peat layer is typically much slower (Lucchese et al. 2010). Resumption of CH₄ emissions following rewetting has been widely reported (Tuittila et al. 2000a, Bortoluzzi et al. 2006, Waddington and Day 2007, Couwenberg 2009, Wilson et al. 2009), although in some cases emissions may be somewhat lower than from comparable natural peatlands (Komulainen et al. 1998, Drösler 2005). In general, N₂O emissions tend to decrease when a peatland is rewetted, as nitrate (NO₃⁻) is fully reduced to nitrogen (N₂) or by plant species out-competing the denitrifying microbes for the available nitrogen (Silvan et al. 2005, Glatzel et al. 2008, Roobroek et al. 2010).

1.2.5 Global Warming Potential

The potential change in GHG fluxes (CO₂ + CH₄ + N₂O) following rewetting is important in terms of calculating the global warming potential (GWP) of the peatland. The GWP methodology is used to compare the integrated radiative forcing, over a specified time horizon (e.g. 20, 100, 500 years), of one unit mass of gas relative to one unit mass of a reference gas (IPCC 2007). CO₂ is assigned a reference value of 1 and emissions of CH₄ and N₂O, for example, can be converted into CO₂-equivalents (CO₂-eq) by multiplying the emission rates (e.g. kg CH₄ ha⁻¹ yr⁻¹) by their GWP value (Box 1.2). The use of GWP methodology has been shown to be less than ideal for expressing the radiative forcing of peatlands as they do not emit isolated emission pulses but instead are sustained and persistent sinks or sources (Frolking et al. 2006).

**Box 1.2. Atmospheric lifetimes and global warming potentials (GWP) relative to CO₂.**

<table>
<thead>
<tr>
<th>GHG</th>
<th>Lifetime (years)</th>
<th>20 years</th>
<th>GWP 100 years</th>
<th>GWP 500 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>Variable</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>CH₄</td>
<td>12</td>
<td>72</td>
<td>25</td>
<td>7.6</td>
</tr>
<tr>
<td>N₂O</td>
<td>114</td>
<td>289</td>
<td>298</td>
<td>153</td>
</tr>
</tbody>
</table>

Source: adapted from IPCC 2007

As noted above, at any given time, natural peatlands may function as either a net GHG source or sink and therefore may produce a net warming (Drösler 2005, Bäckstrand et al. 2010, Drewer et al. 2010) or net cooling impact on the climate (Gorham 1991, Roulet 2005, Dinsmore et al. 2010, Drewer et al. 2010, Koehler et al. 2010). The key drivers in this regard are: (i) the relative strength of either CO₂ or CH₄ fluxes during the particular developmental stage of the peatland (Frolking et al. 2006, Frolking and Roulet 2007) and (ii) the time horizon employed (Whiting and Chanton 2001, Drösler 2005). Drained peatlands have a strong net warming impact on the global climate as a consequence of (i) the large emissions of CO₂ associated with drainage and (ii) the removal of the vegetation to facilitate peat extraction (Cleary et al. 2005, Salm et al. 2009, Wilson et al. 2009). In contrast, studies to date have shown that rewetted peatlands may have either a net cooling (Bortoluzzi et al. 2006) or net warming impact (Drösler 2005, Yli-Petäys et al. 2007, Wilson et al. 2009, Waddington et al. 2010), determined primarily by the magnitude of CH₄ emissions.
1.2.6 Economic Analyses of Peatland Restoration

In recent years, a growing body of research has attempted to place an economic value on ecosystem services, such as biodiversity (Bullock et al. 2008a, Nijkamp et al. 2008, TEEB 2009). The prospective monetary value of wetland restoration in terms of C sequestration has been highlighted in numerous studies (Bullock et al. 2008b, Galatowitsch 2009, Reed et al. 2009, Worrall et al. 2009b), and the potential of restored wetlands to be used as C-offset projects has also been identified (Hansen 2009, Danone Fund for Nature 2010, Jaenicke et al. 2010, Jenkins et al. 2010).

A C offset is a reduction in GHG emissions (tonnes CO$_2$-eq) or an increase in C sequestration that is achieved to compensate for (i.e. offset) GHG emissions occurring from other activities elsewhere (Broekhoff et al. 2008). Offsets can be purchased by countries, companies or individuals and the key criterion for an offset is that the GHG reduction it represents would not have happened anyway, that is, it is ‘additional’ to business-as-usual activity. For example, an individual could reduce the impact of CO$_2$ emissions from activities, such as driving their car, by purchasing offsets from an accredited project that is certified to reduce CO$_2$ by an equivalent amount.

Under the Kyoto Protocol, countries are required to limit or reduce their GHG emissions. The protocol includes market-based mechanisms, such as emissions trading (cap and trade) as a way of helping countries to meet their GHG targets. Under these mechanisms C is assigned a value and traded as a commodity. Currently, C can be traded on either the mandatory markets, which are closely associated with Kyoto Protocol compliance requirements or on the voluntary markets. The volume and price of C traded tend to be considerably higher on the mandatory markets than within the voluntary markets (Hamilton et al. 2010, Jenkins et al. 2010), but the voluntary markets are currently seen as the most promising in terms of selling C credits from peatland restoration, as opportunities for peatland rewetting C-offset projects under compliance markets, such as the Kyoto Protocol, will not be available before 2012$^1$ at the earliest.

One of the most important quality standards on the voluntary market is the Verified Carbon Standard (VCS), which includes Agriculture, Forestry and Other Land Use (AFOLU) in the list of eligible project activities (VCS Association 2008). Originally, it had four categories: (i) Afforestation, Reforestation, Revegetation (ARR), (ii) Agricultural Land Management (ALM), (iii) Improved Forest Management (IFM), and (iv) Reduced Emissions from Deforestation and Degradation (REDD). However, new guidance for the development of peat rewetting or conservation methodologies under the VCS programme has recently been adopted and published (8 March 2011) under the new AFOLU category ‘Peatland Rewetting and Conservation’ (PRC) (www.v-c-s.org).

The use of restored peatlands for C offset projects is attractive in that it offers the prospect for C mitigation by (i) transforming an ecosystem that is a large C source (e.g. an industrial peatland) to one in which the C losses are reduced (avoided losses), and by (ii) increasing the amount of C that may be actively sequestered by the peatland. This has been demonstrated by Jaenicke et al. (2010) who estimated that the rewetting of a tropical peatland in Indonesia could result in avoided losses of around 25 tonnes CO$_2$ ha$^{-1}$ yr$^{-1}$. Similarly, Worrall et al. (2009b) demonstrated that, depending on the price of C used, successful restoration of the C sink function in upland peatlands in the United Kingdom could lead to a profit from C offsetting within 30 years.

1.3 Aims/Objectives

The aims of this EPA funded project were to:

1. Establish a study site at Bellacorick industrial cutaway peatland for the quantification of CO$_2$, CH$_4$ and N$_2$O fluxes, and related environmental variables;

2. Quantify CO$_2$, CH$_4$ and N$_2$O fluxes, and related environmental variables over a 12-month period at a number of microsites within the study site;

3. Model the C gas fluxes using linear and non-linear modelling techniques;

4. Provide an estimate of the C gas balance of the main microsites within the peatland;

5. Estimate the impact of climatic radiative forcing through the calculation of global warming potential (GWP) for each microsite;

6. Determine potential economic benefits accruing from restoration of damaged peatlands in regards to GHG fluxes.

---

$^1$ The present commitment period for the Kyoto Protocol is 2008–2012.
2 Materials and Methods

2.1 Study Site

The study site was located at Bellacorick, Co. Mayo (54° 7' N, 9° 35' W). Formerly an Atlantic blanket bog, the site forms part of the much larger Oweninny bog complex (6,500ha). From 1960 to 2003, the peat was industrially extracted and used in the nearby Bellacorick power station for electricity generation.

Between 1996 and 2002, small-scale rehabilitation test areas were established at Bellacorick and, following the cessation of peat extraction in 2003, a larger-scale rehabilitation plan was implemented in a sequential fashion across the peatland (Bord na Móna 2003). This involved the use of bulldozers and excavators to block drains, create peat ridges to contain the water, and to landscape the peatland surface. This resulted in a number of significant impacts: (i) a rise in the WT level over large areas of the peatland, (ii) the creation of areas of open water and (iii) the recolonisation of the bare peat substrate by a range of vascular and moss communities.

Initial re-colonisation was dominated by *Juncus effusus* (soft rush), which in turn facilitated the establishment of moss species, such as *Polytrichum commune* and *Sphagnum cuspidatum* (Farrell and Doyle 2003). In the wetter parts of the site, *Eriophorum angustifolium* (bog cotton) is found widely, either as a pure stand or in conjunction with *Sphagnum cuspidatum*. The areas of open water and bare peat are decreasing annually as a result of rapid re-colonisation. On the drier edges of the site and along the peat ridges, *Pinus contorta* (lodgepole pine), *Calluna vulgaris* (heather) and *Rhododendron ponticum* (rhododendron) are found.

![Location of the study site at Bellacorick, Co. Mayo.](image1)

![Bellacorick industrial cutaway peatland in 2003. Photo by Catherine Farrell.](image2)

![Bellacorick industrial cutaway peatland in 2009. Areas of bare peat and fossilised timber are still visible throughout the peatland. Photo by David Wilson.](image3)

![Eriophorum angustifolium vegetation in full bloom at Bellacorick industrial cutaway peatland. Photo by David Wilson.](image4)

![Juncus effusus and Eriophorum angustifolium vegetation at Bellacorick industrial cutaway peatland. Photo by David Wilson.](image5)
The residual depth of peat within the study site is around 50cm, with the peat composed mainly of highly humified cyperaceous peat overlying a glacial till substrate (Farrell and Doyle 2003). The pH ranges between 3.8 and 6.4 (Farrell and Doyle 2003) and the C:N ratio is 58.

The climate of the area is characterised by prevailing south-westerly winds and a mean annual rainfall of 1143mm. The mean monthly temperature ranges from 5.6°C in January to 14.1°C in August with a mean annual temperature of 9.3°C (Met Éireann – Belmullet Station, 1961–1990).

2.2 Environmental Variables

In order to examine the impact of rewetting on GHG exchange, 18 permanent sample plots were established within the Bellacorick site. Each sample plot consisted of a stainless steel collar (60 x 60cm) that was inserted to a depth of 30cm into the peat before the start of the study. Perforated polyvinyl chloride (PVC) pipes were inserted adjacent to each sample plot to measure WT position. Wooden boardwalks were built around the sample plots to minimise damage to the vegetation and to prevent compression of the peat during gas sampling. Data loggers (Micrologger Model 4R, Zeta-tec, Durham, UK) were established at the study site and recorded hourly soil temperatures at 5, 10 and 20cm depths. A weather station (WatchDog Model 2400, Spectrum Technologies Inc., Illinois, USA) was also established on the site and programmed to record photosynthetic photon flux density (PPFD, µmol m⁻² s⁻¹) every 10 minutes using Spec 8 Pro software (Spectrum Technologies Inc., Illinois, USA).

2.3 Vegetation Analysis

Following a visual survey of the site, sample plots were established within the main microsites (Table 2.1). These were:

1. Juncus effusus–Sphagnum cuspidatum-dominated communities (n=3);
2. Sphagnum cuspidatum-dominated communities (n=3);
3. Eriophorum angustifolium-dominated communities (n=3);
4. Bare peat (n=3);
5. Open water (n=6).

In order to incorporate the seasonal dynamics of the vegetation into C gas-exchange models, a green area index (GAI) was estimated for each sample plot (Wilson et al. 2007a). This involved measuring the green photosynthetic area of all vascular plants within the sample plot at monthly intervals. Moss coverage in the sample plot was estimated twice yearly. Species-specific model curves were applied to describe the phenological dynamics in vegetation. The models were summed (vascular and moss) to produce a GAI for each sample plot.

<table>
<thead>
<tr>
<th>Microsite</th>
<th>Dominant species</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>Juncus-Sphagnum</td>
<td>Juncus effusus</td>
<td>Polytrichum commune</td>
</tr>
<tr>
<td></td>
<td>Sphagnum cuspidatum</td>
<td>Hydrocotyle vulgaris</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Eriophorum angustifolium</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Juncus bulbosus</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sphagnum capillifolium</td>
</tr>
<tr>
<td>Sphagnum</td>
<td>Sphagnum cuspidatum</td>
<td>Eriophorum angustifolium</td>
</tr>
<tr>
<td>Eriophorum</td>
<td>Eriophorum angustifolium</td>
<td>Polytrichum commune</td>
</tr>
<tr>
<td>Bare peat</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Open water</td>
<td>–</td>
<td>Occasional green algae</td>
</tr>
</tbody>
</table>
2.4 Greenhouse Gas Flux Measurements

2.4.1 Carbon Dioxide

CO$_2$ fluxes were measured from November 2008 to December 2009 at biweekly (summer months) to monthly (winter months) intervals using the static chamber method (Alm et al. 1997) generally between 8 a.m. and 6 p.m. Instantaneous NEE was measured over a range of PPFD (µmol m$^{-2}$ s$^{-1}$) values using a transparent polycarbonate chamber (Figure 2.1, 60 x 60 x 33cm). For each measurement, the chamber was placed in a water-filled channel at the top of the collar and CO$_2$ concentration (ppmv) in the chamber headspace was measured at 15-second intervals over a period of 60–180 seconds using a portable CO$_2$ analyser (EGM-4) (PP Systems, UK). PPFD was measured by a quantum sensor (PAR-1, PP Systems) located at the top of the chamber. At the same time, air temperature within the chamber was recorded. Concurrent with the chamber measurements, soil temperatures (at 5 and 10cm depths) were recorded at each of the collars with a soil temperature probe (ELE International, UK) and WT position relative to the soil surface was manually measured with a water level probe (Eijkelkamp Agrisearch Equipment, The Netherlands).

Following each NEE measurement, the chamber was vented for a short time by removing it from the collar. This was carried out in order to ensure equilibration of the gas concentration. The chamber was then replaced in the collar and covered with an opaque material in order to provide an estimate of ecosystem respiration ($R_{ECO}$).

CO$_2$ flux rates (mg m$^{-2}$ h$^{-1}$) were calculated from the linear change in CO$_2$ concentration in the chamber headspace over time with respect to the chamber volume and temperature. A flux was accepted if the coefficient of determination ($r^2$) was at least 0.90. An exception was made in cases where the flux was close to zero and where the $r^2$ is always low (Alm et al. 2007b).

Positive fluxes indicated a net loss of CO$_2$ and negative values indicated a net uptake of CO$_2$. An estimate of gross photosynthesis ($P_G$) was calculated as the sum of NEE and $R_{ECO}$ values (Alm et al. 1997).

2.4.2 Methane and Nitrous Oxide

CH$_4$ and N$_2$O fluxes were measured at monthly intervals using the static chamber method (Crill 1991), which consisted of a polycarbonate chamber (60 x 60 x 25cm) equipped with a battery-operated fan, which mixed the air within the chamber headspace. Four 50ml samples were withdrawn into 60ml polypropylene syringes (Figure 2.2). The measurement period was increased to 40 minutes during wintertime when low fluxes were expected (Laine et al. 2007b).

During each measurement, air temperature inside the chamber, soil temperature (at 5 and 10cm depths) and WT outside the chamber were recorded. Gas samples were analysed for CH$_4$ and N$_2$O concentrations within 24 hours of collection with a gas chromatograph with an attached auto-sampler unit (Shimadzu GC-2014, LAL, Gottingen, Germany) using a flame ionisation detector (FID) and an electron capture detector (ECD). Detector temperatures were 200°C (FID) and 310°C (ECD) and the oven temperature was 70°C (Loftfeld et al. 1997). Nitrogen was used as the carrier gas (22 ml min$^{-1}$). CH$_4$ (1.8, 3.99 and 10ppm) and N$_2$O standards (0.30, 0.80 and 9.96ppm) from BOC Gases Ireland Ltd were used. Gas peaks were integrated using Peak Simple software.
(SRI Inc. Silicon Valley, California, USA). Fluxes (mg m\(^{-2}\) h\(^{-1}\)) were calculated from the linear change in gas concentration as a function of time, chamber volume and temperature. A flux was accepted if the \(r^2\) was at least 0.90. An exception was made in cases where the flux was close to zero and where the \(r^2\) is always low (Alm et al. 2007b). Positive values indicated a loss of CH\(_4\) and N\(_2\)O to the atmosphere and negative flux values indicated CH\(_4\) and N\(_2\)O uptake.

### 2.5 Greenhouse Gas Flux Modelling Methods

#### 2.5.1 Carbon Dioxide

##### 2.5.1.1 Gross photosynthesis (\(P_G\))

Gross photosynthesis (\(P_G\)) is strongly dependent on irradiation (PPFD) and is commonly described by the Michaelis-Menten function showing a hyperbolic response approaching an asymptotic maximum. The seasonal variation in the photosynthetic capacity of the vegetation is described by GAI and incorporated into the model in a manner similar to Wilson et al. (2007b) (Eqn 2.1, 2.2 and 2.3).

\[
P_G = P_{max} \left( \frac{PPFD}{PPFD + k_{PPFD}} \right) * GAI * \left( \exp\left( -0.5 \left( \frac{(WTD-a)}{b} \right) \right) \right)
\]

(Eq. 2.1)

\[
P_G = P_{max} \left( \frac{PPFD}{PPFD + k_{PPFD}} \right) * GAI
\]

(Eq. 2.2)

\[
P_G = P_{max} \left( \frac{PPFD}{PPFD + k_{PPFD}} \right) * \left( 1 - \exp\left(-a*GAI\right) \right)
\]

(Eq. 2.3)

Where:

- \(P_G\) is gross photosynthesis,
- \(P_{max}\) is maximum photosynthesis,
- \(PPFD\) is photosynthetic photon flux density,
- \(k_{PPFD}\) is the PPFD value at which \(P_G\) reaches half its maximum,
- GAI is green area index,
- WTD is water table depth, and
- \(a\) and \(b\) are model parameters.

##### 2.5.1.2 Ecosystem respiration (\(R_{ECO}\))

Respiration rates are strongly influenced by both temperature and the water table. A linear model was applied between log-transformed \(R_{ECO}\) and soil temperature at 5cm depth (\(T_{5cm}\)) and WTD (Eq. 2.4).

\[
\ln R_{ECO} = a + (b * T_{5cm}) + (c * WTD)
\]

(Eq. 2.4)

For the bare peat microsite, a sigmoidal curve with WTD as the explaining variable was used (Eq. 2.5).

\[
R_{ECO} = \frac{a}{\left(1 + \exp\left(-(WTD - a)/b\right)\right)}
\]

(Eq. 2.5)

Where:

- \(R_{ECO}\) is ecosystem respiration,
- \(T_{5cm}\) is temperature at 5cm depth in the peat,
- WTD is water table depth, and
- \(a\), \(b\) and \(c\) are model parameters.

#### 2.5.2 Methane (CH\(_4\))

CH\(_4\) fluxes were closely related to the soil temperature at 10cm depth (\(T_{10cm}\)) and to either WTD (Eq. 2.6) or GAI (Eq. 2.7):

\[
CH_4 = (\exp(a * T_{10cm})) * (b + (c * WTD))
\]

(Eq. 2.6)

\[
CH_4 = (\exp(a * T_{10cm})) * (b + (c * GAI))
\]

(Eq. 2.7)

Where:

- \(T_{10cm}\) is temperature at 10cm depth in the peat,
- WTD is water table depth,
- GAI is the green area index,
- \(a\), \(b\) and \(c\) are model parameters.

Gross photosynthesis (\(P_G\)), ecosystem respiration (\(R_{ECO}\)) and CH\(_4\) were parameterised separately for each microsite (Table 3.1). Model coefficients were estimated either using the Levenberg-Marquardt multiple non-linear regression technique or multiple linear regression techniques (SPSS, Version 15.0 for Windows, SPSS Inc. Chicago, USA). One-third of the data was randomly removed from all data sets and used to test the models independently. Model evaluation was based on the following criteria: (i) statistically significant model parameters (p<0.05), (ii) lowest possible standard error of the model parameters and (iii) highest possible coefficient of determination (adjusted \(r^2\)) (see Laine et al. 2009).

#### 2.6 Reconstruction of Annual CO\(_2\)--C Balance

The response functions estimated for \(P_G\) and \(R_{ECO}\) were used for the seasonal reconstruction of NEE. In combination with an hourly time series of (i) PPFD and \(T_{5cm}\) recorded by the weather station and data loggers, (ii) modelled GAI and (iii) WTD depths linearly interpolated from weekly measurements, \(P_G\) and \(R_{ECO}\) fluxes were reconstructed for each sample plot NEE was then calculated on an hourly basis as follows: NEE=\(P_G-R_{ECO}\) (Alm et al. 1997).
Negative NEE values indicated a net uptake of CO$_2$ from the atmosphere to the peatland and positive values indicated a net loss of CO$_2$ to the atmosphere. The annual CO$_2$–C balance (g C m$^{-2}$ yr$^{-1}$) was calculated for each sample plot by integrating the hourly NEE values over a 12-month period (1 January 2009 to 31 December 2009). An average value (± standard deviation) for each microsite was calculated from the annual CO$_2$–C balance of the sample plots within the microsite.

2.7 Reconstruction of Annual CH$_4$–C
The response functions estimated for CH$_4$ were used for the seasonal reconstruction of CH$_4$ fluxes. In combination with an hourly time series of (i) $T_{10cm}$, recorded by the data loggers, (ii) modelled GAI and (iii) WT depths linearly interpolated from weekly measurements, hourly CH$_4$ fluxes were reconstructed for each sample plot and integrated over a 12-month period (1 January 2009 to 31 December 2009). An average value (± standard deviation) for each microsite was calculated from the annual CH$_4$–C balance of the sample plots within the microsite.

2.8 Global Warming Potential Calculations
Global warming potential (GWP) (t CO$_2$-eq ha$^{-1}$ yr$^{-1}$) was calculated for each of the microsites in the study. A GWP (100-year horizon) of 1, 25 and 298 for CO$_2$, CH$_4$ and N$_2$O respectively was employed (IPCC 2007). CO$_2$, CH$_4$ and N$_2$O were converted into CO$_2$-eq values by multiplying annual flux rates with the respective GWP. Negative GWP values indicate that the microsite was a net GHG sink and had a net cooling effect on the climate. Positive values indicate that the microsite was a net GHG source and had a net warming effect on the climate.

2.9 Economic Analyses
The impact of restoration on the value of C at Bellacorick was examined through a series of timeline scenarios that followed the change in land use from the cessation of peat extraction, through rewetting and on to the present day. Greenhouse gas flux values (t CO$_2$-eq ha$^{-1}$ yr$^{-1}$) from this study and from literature (Wilson et al. 2009) were used to estimate the annual GHG flux for each timeline. The price of C on the EU Emissions Trading Scheme (ETS) has fallen considerably since 2009 and currently (2012) trades at €15 t CO$_2$-eq (European Climate Exchange, 2010). For this exercise, a mid-range price of €20 t CO$_2$-eq was used.

**Timeline scenarios**

$T_{zero}$: Peat extraction has ceased at Bellacorick and the peatland is characterised by the absence of vegetation. Drainage ditches are still functioning and, as a result, the WT level is on average 25cm below the peat surface (Wilson et al. 2009).

$T_1$: A year later, Bellacorick has been rewetted by the blocking of the drainage ditches. As a consequence of landscaping the peat surface, the WT level varies considerably throughout the peatland, on average 20cm above the peat surface in depressions to around 0.5cm below the peat surface on elevated areas. The peatland is covered by 50% bare peat and 50% open water.

$T_{present}$: Six years after rewetting, the surface of the peatland has been largely re-colonised by vegetation. Bare peat areas have declined to around 2% and open water to 5%. The main vegetation communities are Juncus-Sphagnum (30%), Sphagnum (30%), Eriophorum (30%) and others (3%).
3 Results

3.1 Environmental Variables

Photosynthetic photon flux density (PPFD) values exhibited strong diurnal and seasonal variation (Fig. 3.1). Daily PPFD values were generally highest in the period from midday to 2 p.m. and lowest at night (zero). Seasonally, PPFD increased steadily from January, peaked in mid-June (~2000µmol m⁻² sec⁻¹) and declined towards December. During the period of the study, the mean annual air temperature was 10.5°C which is a deviation from the long-term average value by +9%. Annual rainfall was 1326mm (Met Éireann, Belmullet Station), that is, a deviation from the long-term average value by +16%.

For the duration of the study, the WT level varied significantly between microsites (Fig. 3.2). The highest WT were recorded in the open-water microsites (~25cm above the peat surface) and the lowest in the bare peat (15cm below the peat surface). At all microsites, the WT remained constant throughout the duration of the study, with the exception of a noticeable dip in WT levels in June in response to lower than average rainfall levels (Fig. 3.1).

A strong, unimodal seasonality in the GAI was observed within all vegetated microsites (Fig. 3.3). Green area index (GAI) values increased during the spring, reaching a maximum in June/July for the

![Figure 3.1](image)

Figure 3.1. Climate data for Bellacorrick, Co. Mayo in 2009. (a) Photosynthetic photon flux density (PPFD; µmol m⁻² sec⁻¹), (b) monthly air temperature (°C) and (c) monthly rainfall (mm) (Met Éireann – Belmullet Station).
Juncus-Sphagnum and Eriophorum microsites, and in September for the Sphagnum microsite. Thereafter they declined, although GAI values were still significant during the winter months (November–February) at the Juncus-Sphagnum and Sphagnum microsites as a consequence of the evergreen growth strategy of these communities.

3.2 Greenhouse Gas Flux Modelling

The strength of the relationship between CO₂ fluxes and the environmental variables varied between the microsites. A close relationship between gross photosynthesis (P₀) and PPFD was observed for all the microsites. The addition of GAI further improved the
Table 3.1. Estimated parameter values for gross photosynthesis ($P_G$), ecosystem respiration ($R_{ECO}$) and methane ($CH_4$) models for each microsite. Standard error in parentheses. Coefficient of determination ($r^2$) values and equation number are shown. P values for all parameters < 0.005.

<table>
<thead>
<tr>
<th>Model parameters</th>
<th>Juncus-Sphagnum</th>
<th>Sphagnum</th>
<th>Eriophorum</th>
<th>Bare peat</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_e$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P_{max}$</td>
<td>1135 (124)</td>
<td>711 (123)</td>
<td>3709 (473)</td>
<td>-</td>
</tr>
<tr>
<td>$k_{PPFD}$</td>
<td>830 (169)</td>
<td>845 (286)</td>
<td>1048 (270)</td>
<td>-</td>
</tr>
<tr>
<td>$a$</td>
<td>-3.04 (3.24)</td>
<td>-</td>
<td>1.63 (0.36)</td>
<td>-</td>
</tr>
<tr>
<td>$b$</td>
<td>12.84 (3.56)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$r^2$</td>
<td>0.80</td>
<td>0.64</td>
<td>0.73</td>
<td>-</td>
</tr>
<tr>
<td>Equation No.</td>
<td>2.1</td>
<td>2.2</td>
<td>2.3</td>
<td></td>
</tr>
<tr>
<td>$R_{ECO}$</td>
<td></td>
<td></td>
<td></td>
<td>161.1 (22.2)</td>
</tr>
<tr>
<td>$a$</td>
<td>3.4</td>
<td>2.89 (0.64)</td>
<td>3.41 (0.107)</td>
<td></td>
</tr>
<tr>
<td>$b$</td>
<td>0.154</td>
<td>0.157 (0.024)</td>
<td>0.13 (0.01)</td>
<td>-4.18 (0.77)</td>
</tr>
<tr>
<td>$c$</td>
<td>-0.107</td>
<td>-0.069 (0.042)</td>
<td>-0.061 (0.004)</td>
<td>-11.688 (2.01)</td>
</tr>
<tr>
<td>$r^2$</td>
<td>0.74</td>
<td>0.59</td>
<td>0.58</td>
<td>0.91</td>
</tr>
<tr>
<td>Equation No.</td>
<td>2.4</td>
<td>2.4</td>
<td>4</td>
<td>2.5</td>
</tr>
<tr>
<td>$CH_4$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$a$</td>
<td>0.248 (0.048)</td>
<td>0.21 (0.032)</td>
<td>0.026 (0.025)</td>
<td></td>
</tr>
<tr>
<td>$b$</td>
<td>0.061 (0.041)</td>
<td>0.111 (0.065)</td>
<td>0.281 (0.093)</td>
<td></td>
</tr>
<tr>
<td>$c$</td>
<td>0.005 (0.001)</td>
<td>0.004 (0.004)</td>
<td>0.349 (0.165)</td>
<td></td>
</tr>
<tr>
<td>$r^2$</td>
<td>0.74</td>
<td>0.77</td>
<td>0.61</td>
<td></td>
</tr>
<tr>
<td>Equation No.</td>
<td>2.6</td>
<td>2.6</td>
<td>2.7</td>
<td></td>
</tr>
</tbody>
</table>

explanatory power of the models (data not shown). A clear relationship between WT and $P_o$ has been noted in other studies (Tuittila et al. 2004) and the incorporation of WT (Eq. 2.1) improved the performance of the $P_o$ model for the Juncus–Sphagnum microsite ($r^2=0.80$). However, no statistically significant relationship between $P_o$ and WT was observed for the other microsites. Modelling of CO$_2$ exchange proved problematic with the open-water microsite, as no statistically significant relationship between CO$_2$ fluxes and environmental variables was observed. Instead, monthly mean values were calculated and integrated over the 12-month study period. Measured N$_2$O fluxes throughout the study period were negligible and below the detection level of the equipment (data not shown).

3.3 Annual CO$_2$–C Balance

In 2009, the vegetated microsites sequestered on average 279±246g CO$_2$-C m$^{-2}$ yr$^{-1}$. Average values for the individual microsites were 106±3.66g CO$_2$-C m$^{-2}$ yr$^{-1}$ for Sphagnum, 143±8.85g CO$_2$-C m$^{-2}$ yr$^{-1}$ for Juncus–Sphagnum and 577±160.69g CO$_2$-C m$^{-2}$ yr$^{-1}$ for the Eriophorum microsite (Fig. 3.4). There was considerable spatial variation in NEE both within and between microsites, driven by differences in WT level and GAI. Very high NEE values were observed within
the Eriophorum microsite, primarily as a result of high levels of $P_G$ and moderate losses of $CO_2$-C from $R_{ECO}$. Lower NEE values were seen within the Juncus-Sphagnum and Sphagnum microsites, mainly because of lower $P_G$ values (i.e. lower primary productivity). However, $R_{ECO}$ values within those microsites were also very low as a consequence of high WT positions. In general, $R_{ECO}$ values at all microsites were relatively low (Fig. 3.4). NEE for the open-water microsite was estimated to be 53 g $CO_2$-C m$^{-2}$ yr$^{-1}$. However, this result should be treated with caution, as the values for the open-water microsite are monthly mean values with no ecological foundation and limited statistical confidence.

$CO_2$-C emissions from the bare-peat microsite (~40 g $CO_2$-C m$^{-2}$ yr$^{-1}$) are similar to values reported for other rewetted cutaway peatlands (Bortoluzzi et al. 2006, Kivimäki et al. 2008) but are considerably lower than those reported for bare peat extraction areas (see Table 1.1), highlighting the importance of WT management in minimising $CO_2$ emissions. The maintenance of high WT levels throughout the year at the study site ensured that decomposition of the residual peat remained low and that $R_{ECO}$ was largely dominated by autotrophic respiratory losses.

### 3.4 Annual CH$_4$–C Balance

The vegetated microsites in this study released an average of 10.1±3.6 g CH$_4$-C m$^{-2}$ yr$^{-1}$ to the atmosphere in 2009. Average values for the individual microsites were 0.11 g CH$_4$-C m$^{-2}$ yr$^{-1}$ for the bare peat, 0.29 g CH$_4$-C m$^{-2}$ yr$^{-1}$ for the open water, 5.38±1.43 g CH$_4$-C m$^{-2}$ yr$^{-1}$ for Eriophorum, 11.83±0.27 g CH$_4$-C m$^{-2}$ yr$^{-1}$ for Juncus-Sphagnum and 13.1±0.15 g CH$_4$-C m$^{-2}$ yr$^{-1}$ for Sphagnum (Fig. 3.5). The persistently high WT levels throughout the year (in particular during the growing season) created optimal conditions for the CH$_4$ production. The highest CH$_4$ emissions in this study occurred within the vegetated microsites where the WT level remained highest (i.e. Sphagnum). The strong relationship between high WT levels and the availability of fresh organic matter (litter and root exudates) on the one hand and CH$_4$ emissions on the other has been observed in many studies (Bubier 1995, Saarnio et al. 1997, Ström et al. 2003, Saarnio et al. 2004, Wilson et al. 2009).
3.5 Global Warming Potential for the Study Site

For the period of the study, the microsites had either a net warming impact (GHG source) or a net cooling impact (GHG sink) on the climate over a 100-year horizon (Table 3.2). The open-water microsite was the largest GHG source, releasing 2.04 t CO$_2$-eq ha$^{-1}$ yr$^{-1}$ to the atmosphere. However, as stated above, very high uncertainties are to be associated with this value because of the limited statistical treatment of the data from the open-water microsite. Both the bare peat (1.45 t CO$_2$-eq ha$^{-1}$ yr$^{-1}$) and Sphagnum (0.46 t CO$_2$-eq ha$^{-1}$ yr$^{-1}$) microsites were GHG sources for 2009. In the latter, CH$_4$ emissions were the dominant component of the GWP. The Juncus-Sphagnum (1.30 t CO$_2$-eq ha$^{-1}$ yr$^{-1}$) and Eriophorum (19.33 t CO$_2$-eq ha$^{-1}$ yr$^{-1}$) microsites were GHG sinks. In particular, Eriophorum had a strong cooling impact on the climate, driven by large CO$_2$ sequestration rates and moderate CH$_4$ emissions. Studies elsewhere have shown that GWP may not be the most appropriate measure for assessing the contribution of peatlands to the global climate, given that fluxes are rarely pulse events and vary considerably over time (Frolking et al. 2006, Frolking and Roulet 2007). Similarly, research has shown that the choice

Table 3.2. Global warming potential (GWP, t CO$_2$-eq ha$^{-1}$ yr$^{-1}$, 100 year horizon) for the microsites at Bellacorick, Co. Mayo in 2009. Standard deviation in parentheses. Negative values indicate that the microsite was a net greenhouse gas (GHG) sink and had a net cooling impact on the climate for the period of the study. Positive values indicate that the microsite was a net GHG source and had a net warming impact on the climate for the period of the study.

<table>
<thead>
<tr>
<th>Microsite</th>
<th>CO2</th>
<th>CH4</th>
<th>N2O</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(t CO$_2$-eq ha$^{-1}$ yr$^{-1}$)</td>
<td>(t CO$_2$-eq ha$^{-1}$ yr$^{-1}$)</td>
<td>(t CO$_2$-eq ha$^{-1}$ yr$^{-1}$)</td>
<td>(t CO$_2$-eq ha$^{-1}$ yr$^{-1}$)</td>
</tr>
<tr>
<td>Juncus-Sphagnum</td>
<td>-5.23 (0.32)</td>
<td>+3.93 (0.09)</td>
<td>0</td>
<td>-1.30</td>
</tr>
<tr>
<td>Sphagnum</td>
<td>-3.88 (0.13)</td>
<td>+4.34 (0.05)</td>
<td>0</td>
<td>+0.46</td>
</tr>
<tr>
<td>Eriophorum</td>
<td>-21.12 (5.89)</td>
<td>+1.79 (0.48)</td>
<td>0</td>
<td>-19.33</td>
</tr>
<tr>
<td>Bare peat</td>
<td>+1.41 (0.22)</td>
<td>+0.037</td>
<td>0</td>
<td>+1.45</td>
</tr>
<tr>
<td>Open water</td>
<td>+1.94</td>
<td>+0.096</td>
<td>0</td>
<td>+2.04</td>
</tr>
</tbody>
</table>
of time horizon employed in the GWP calculation can influence the GHG sink/status of the peatland (Joosten and Clarke 2002, Drösler 2005, Höper et al. 2008, Drewer et al. 2010). For example, the use of the 500-year horizon in this study would have resulted in all the vegetated microsites producing a net cooling effect on the climate.

3.6 Economic Analyses

Considerable variation was found in the value of C between the three timeline scenarios. At $T_{\text{zero}}$, when peat extraction at Bellacorick has ceased, Wilson et al. (2009) estimated that around 11t CO$_2$-eq ha$^{-1}$ yr$^{-1}$ would be emitted to the atmosphere from bare peat areas where the WT level remains low. At a C price of €20 t CO$_2$-eq, this equates to a total loss of €220 ha$^{-1}$ for the $T_{\text{zero}}$ scenario (Fig. 3.6). When the peatland is rewetted ($T_1$), emissions decreased significantly as a result of higher WT levels (values from the bare peat microsite in this study) and the cost of C emitted from the peatland decreased to around €35 ha$^{-1}$, resulting in an avoided loss of C of €186 ha$^{-1}$. In the time from rewetting until this study ($T_{\text{present}}$), recolonisation of the peatland by a range of vegetation communities, combined with the maintenance of a high WT level led to a situation whereby the peatland is now a net GHG sink and the value of C sequestered for $T_{\text{present}}$ is around €118 ha$^{-1}$. This is added to the avoided loss of C of €220 ha$^{-1}$ to give a total of €318 ha$^{-1}$ for the year of this study ($T_{\text{present}}$).

Clearly, these values are subject to change in regard to the upward or downward movement in the traded price of C. However, the differences between the three scenarios are driven not by the traded price of C but by the magnitude of measured GHG fluxes. In the absence of data for the years between $T_1$ and $T_{\text{present}}$, it is impossible to estimate the point when the peatland switched from acting as a net GHG source to a net GHG sink, nor indeed to assess the magnitude of annual fluxes in that time period. Nevertheless, it is likely that the peatland would have continued along a development trajectory that would have resulted in continued C savings through avoided losses (Fig. 3.6, dotted line). This is estimated to have mitigated around 75.3t CO$_2$-eq ha$^{-1}$ (€1506 ha$^{-1}$) for the time period $T_1$ to $T_{\text{present}}$. Furthermore, by moving from $T_{\text{zero}}$ to $T_1$, the investment in rewetting is paid back by emissions reductions within two years.

![Graph showing economic analyses](image)

Figure 3.6. Value of C (€ ha$^{-1}$ yr$^{-1}$) for timeline scenarios, $T_{\text{zero}}$, $T_1$, and $T_{\text{present}}$. Dotted line indicates predicted avoided costs for the years between scenarios. A C price of €20t CO$_2$-eq is assumed. Greenhouse gas (GHG) values taken from literature and this study.
4 Discussion and Conclusions

Since the 1990s, the impact of restoration on C gas dynamics in industrial cutaway peatlands has received considerable attention in other countries but has been largely neglected in Ireland. Instead, studies in this country have focused on the C sequestration potential of alternative land-use options, such as afforestation, natural regeneration and amenity wetlands (Byrne et al. 2007a, Byrne et al. 2007b, Wilson et al. 2007b, Wilson et al. 2009). As such, this study represents the first investigation of the C sequestration potential of a restored industrial cutaway peatland in Ireland.

The results presented in this report suggest that the rewetting actions and subsequent re-colonisation of the highly degraded peatland at Bellacorick have been successful in creating suitable conditions for C sequestration. There are a number of reasons why the CO$_2$–C sink values for 2009 are at the upper range of reported values for rewetted peatlands (Tuittila et al. 1999, Yli-Petäys et al. 2007, Kivimäki et al. 2008).

Firstly, given the successional stage of the peatland, biomass and litter are still increasing rapidly but over time will reach a steady-state equilibrium in terms of the rate of C sequestration. After that, the accumulation of organic matter (and the C therein) in a new peat layer is typically much slower (Lucchese et al. 2010). Secondly, under a mild temperate climate, the growing season is considerably longer than in boreal climates, providing an extended timeframe for C uptake (Wilson et al. 2007a).

Combined with the wide coverage of evergreen moss species, such as Sphagnum cuspidatum, at the study site, photosynthetic activity and hence C uptake may take place even during the winter months (Fig. 3.3).

Thirdly, the relatively low ecosystem respiration (R$_{eco}$) values observed during the study further increase the margin between net C losses and net C gains. Research has shown a correlation between the nutrient status and the rate of decomposition of the peat (Couwenberg et al. 2008, Bayley et al. 2009). The high C:N ratio recorded at the site indicates that the residual peat at Bellacorick is nutrient poor and may result in lower microbial decomposition rates, and therefore, lower CO$_2$ production (Francez et al. 2000).

The moderate-high CH$_4$-C emissions reported here indicate that, in terms of C gas functioning, the peatland is now more reminiscent of a fen (historical precursor to a bog) than a bog ecosystem (Nykänen et al. 1998, Huttunen et al. 2003, Rinne et al. 2007, Drewer et al. 2010). Aerenchymatic plant species have been associated with high CH$_4$ emissions (Bubier 1995, Frenzel and Karofeld 2000, Riutta et al. 2007a). However, in this study, the highest CH$_4$ emissions occurred within the Sphagnum-dominated microsite, where Eriophorum angustifolium (an aerenchymatic species) was a minor component than in microsites dominated by aerenchymatic species (Juncus-Sphagnum and Eriophorum). Other studies have reported similar findings (e.g. Roura-Carol and Freeman 1999, Dinsmore et al. 2009a, Dinsmore et al. 2009b), linking increased oxidation of the rhizosphere by aerenchymatic plants to reduced CH$_4$ emissions (Fritz et al. 2011).

Fluvial C fluxes were not quantified in this study. Work by Waddington et al. (2008) at a restored peatland in Canada estimated the annual export of dissolved organic carbon (DOC) at between 3.4 and 4.8g C m$^{-2}$, with higher exports occurring in wetter years. Furthermore, they estimated that DOC losses from the restored site were significantly lower than losses from an adjacent cutover peatland.

Restoration at Bellacorick has not succeeded in returning the peatland to the state that existed immediately prior to peat extraction. At Bellacorick, the vegetation communities are not typical of those found in Atlantic blanket bogs, which are dominated by plant species such as Schoenus nigricans and Molinia caerulea (Farrell and Doyle 2003, Sottocornola et al. 2008). Similarly, blanket bogs have been shown to be modest sinks for CO$_2$-C (Koehler et al. 2010, Sottocornola and Kiely 2010) and low CH$_4$-C sources (Laine et al. 2007b, Koehler et al. 2010). In contrast, C gas fluxes at Bellacorick for 2009 were characterised by large sinks/sources. Notwithstanding this, restoration has instead started a new process, along a new developmental trajectory (Vasander et al. 2003). At this point in time,
it is difficult to determine the direction or speed that this new trajectory might follow. Given that so many of the environmental conditions that were present when the original peatland developed (e.g. climate, vegetation, hydrology, etc.) are unlikely to be present today (Charman 2002, Holden 2005), a number of developmental trajectories, with major implications for C sequestration, may develop over time (Holden 2005).

In the absence of active restoration measures, such as drain blocking and re-colonisation, there is a high probability that the cutaway peatland that existed at T_{zero} in the current research timeline scenarios would continue to be a strong net CO_{2} source in the short and medium term as the peat is oxidised (Waddington et al. 2001, Waddington et al. 2002, Wilson et al. 2007b, Wilson et al. 2009). Studies have demonstrated that this type of ecosystem has a strong warming impact on the climate (Wilson et al. 2009) and the potential value of C emitted (€ ha\(^{-1}\) yr\(^{-1}\)) may be high (Fig. 3.6). This may decrease slightly over time as the more easily decomposable fractions of the peat are oxidised in the early years. With minimal human intervention, natural succession will take place and the cutaway will be re-colonised by a range of dryland plant species. In Ireland, this has generally resulted in the establishment of birch/willow scrub on drained industrial cutaways (Renou et al. 2006). However, studies have shown that these ecosystems may be net C gas sources, primarily as a consequence of high soil CO_{2} emissions and low primary productivity (von Arnold et al. 2005, Byrne et al. 2007b).

At Bellacorick, the direction of the new trajectory will be governed to a large extent by management and climatic factors. Climate modelling exercises have predicted that precipitation distribution and frequency will change in Ireland over the coming decades (Sweeney et al. 2002, Sweeney et al. 2008). During the period of the study, rainfall was 16% higher than the long-term average. In fact, 2009 was the eighth wettest year since 1957 (Fig. 4.1) and this undoubtedly contributed to the high WTs observed at the study site. If annual precipitation levels increase over the next decades then it is possible that the peatland at Bellacorick may continue along a developmental trajectory towards a bog ecosystem. Similarly, if rainfall frequency and distribution are below the long-term average, it is likely that the strength of the C sink function may be reduced, particularly as the amount of C stored in the biomass will begin to reach a steady-state C sequestration saturation point (Anderson et al. 2008). Prolonged periods of drought may result in the peatland undergoing a second wave of re-colonisation, this time by dryland plant species, which might lead to further drying of the peatland. The impact of future climate

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**Figure 4.1.** Rainfall (mm yr\(^{-1}\)) at Belmullet Meteorological Station, Co. Mayo 1957–2009. Data from Central Statistics Office (CSO).
change on peatlands in general is highly uncertain as a consequence of response variations both between and within individual peatlands (Moore et al. 1998, Welker et al. 2004) and potential positive and negative feedbacks driven by changes in climate (Bridgham et al. 1995). Work by Jones et al. (2006) has predicted that around 40% of Irish peatlands could disappear over the coming decades as a consequence of climate change. Given that degraded peatlands are likely to be more vulnerable to external changes than natural peatlands, well-informed management decisions will be critical in maintaining optimal conditions for C sequestration. These may involve the removal of colonising trees to prevent increased rates of evapotranspiration and the subsequent drying-out of the peatland, as well as the maintenance of drainage dams and bunds to ensure that the WT remains high throughout the peatland (Schumann and Joosten 2008).

As noted above, the potential for restored peatlands as a climate-mitigation option has been discussed widely in recent years (Couwenberg et al. 2008, Parish et al. 2008, Joosten and Couwenberg 2009), particularly at the UNFCCC Conference of the Parties (COP) meetings. The voluntary and mandatory C trading schemes that are currently in operation imply that C, both stored and annually sequestered, could have an economic and tradable value if they can be reported and verified accurately (Galatowitsch 2009, Joosten and Couwenberg 2009, Worrall et al. 2009b). Given the considerable C savings achieved in the years since rewetting at Bellacorick, the suitability of restored industrial peatlands as C offset projects is good provided (i) the restoration process is as successful on degraded peatlands elsewhere and (ii) the price of C traded on the markets is attractive.

In conclusion, restoration of degraded peatlands offers a number of important benefits in terms of C gas exchange. Firstly, the re-establishment and, more importantly, the maintenance of hydrological conditions characteristic of natural peatlands minimises CO₂ emissions from the peat and leads to a potential C saving or avoided loss (T₁ scenario, Figure 3.6). Furthermore, the re-establishment of the C sequestration capability of the peatland through re-colonisation by appropriate vegetation communities may further reduce C losses from the peatland and/or enhance C storage (Tₚresent scenario, Fig. 3.6). As this study represents a single 12-month period, further investigation is required as uncertainties are obviously high and care should be taken in interpreting the values reported. Inter-annual variations in C gas exchange are a strong feature of peatlands in general, driven mainly by variations in climatic inputs. Long-term monitoring is essential to more accurately assess the potential for this peatland, in particular, and restored peatlands, in general, to sequester C.
5 Observations and Recommendations

Observation 1: Drained industrial cutaway peatlands are a significant net GHG source. Practical rehabilitation measures, such as a simple rewetting programme at Bellacorick, resulted in a sharp decrease in CO₂ emissions and minimal CH₄ emissions from bare-peat areas. Furthermore, the initial rewetting is likely to have reduced the GWP of the site by 87% (i.e. the peatland had a less warming impact on the climate).

Recommendation: Management plans for the cutaway should be in place in advance of the cessation of peat extraction. For cutaways that have the potential to be restored/rewetted, drainage ditches should be blocked as soon as possible following the cessation of peat extraction at an individual peatland to minimise potential emissions of CO₂ from the peat and, thereby, lower the GWP.

Observation 2: The rewetted cutaway peatland at Bellacorick, which developed typical peat-forming vegetation, was a strong CO₂-C sink and CH₄-C source for 2009. N₂O-N fluxes were zero. The GWP of vegetated areas varied from net cooling to net warming over a 100-year horizon.

Recommendation: Given the very dynamic nature of vegetation change at the peatland, and the strong inter-annual variation in GHG fluxes of peatlands in general, long-term monitoring of GHG fluxes is essential to accurately quantify the changes that are likely to take place at Bellacorick in the future.

Observation 3: The results from this study have shown that the peatland has regained some of the ecological functioning characteristic of an earlier stage in its development trajectory. The restoration of the C sink function has occurred over a short time frame following initial rewetting. However, it is not certain at this point in time as to what ecological direction the peatland might take in the future.

Recommendation: Management decisions can influence the future direction to some extent. Maintenance of the site (blocking drains, removal of trees, etc.) is essential to ensure that WT levels remain appropriately high at the site, particularly throughout the main growing season (April to October). Absence of management input may lead to a progressive change in the site towards a dryland species cover.

Observation 4: Rewetting of drained peatlands is likely to be addressed in future climate talks and the C credits accrued may be seen as a possible climate mitigation option. Currently, there are no good practice guidelines available for the development of peat-rewetting methodologies under either the mandatory or voluntary markets. However, the IPCC has signalled that it intends to address this area shortly, and the VCS programme has adopted a Peatland Rewetting and Conservation (PRC) module in its AFOLU standard which allows voluntary C trading schemes.

Recommendation: The support for credits to be allowed for C storage through peatland conservation or restoration should be supported by Ireland in the negotiation of the Kyoto Protocol, and by active engagement in the development of good practice guidelines for peatland rewetting. In this regard, long-term monitoring of GHG fluxes is essential in order to accurately quantify, report and verify.

Observation 5: Rewetting of drained peatlands can lead to restoration of functional peatland aspects, such as the return of typical peatland species, which in turn may lead to the restoration of peat-formation and the C-sink function. This is not possible in all degraded peatland sites, but is a practical and a relatively simple measure in some sites.

Recommendation: The restoration potential of individual degraded peatlands and, in particular, the industrial cutaway bogs, needs to be assessed at the field-site level to determine the most cost-effective approach, the maximum areas of benefit and appropriate measures to employ.
References


Acronyms and Annotations

CH$_4$ Methane
CO$_2$ Carbon dioxide
DOC Dissolved organic carbon
EU ETS European Union Emissions Trading Scheme
GAI Green area index
GHG Greenhouse gas
GWP Global warming potential
IPCC Intergovernmental Panel for Climate Change
LULUCF Land use, land use change and forestry
N$_2$O Nitrous oxide
NEE Net ecosystem exchange
P$_G$ Gross photosynthesis
POC Particulate organic carbon
PPFD Photosynthetic photon flux density
PRC Peatland Rewetting and Conservation
r$^2$ coefficient of determination
R$_{\text{ECO}}$ Ecosystem respiration
SBSTA Subsidiary Body for Scientific and Technological Advice
Tg Terragrams
UNFCCC United Nations Framework Convention on Climate Change
VCS Voluntary Carbon Standard
WT Water table
WTD Water table depth
An Ghníomhaireacht um Chaomhnú Comhshaoil

Is í an Gníomhaireacht um Chaomhnú Comhshaoil (EPA) comhlacht a heachtaít a chosnaionn an comhsaoil do mhuintir na tíre go léir. Rialaimid agus déanaímid maoirísí ar ghníomhaíochtaí atá d’fhéadfadh truailliú a chruthú murach sin. Cníntimid go bhfuil eolas cruinn ann ar threoicht comhsaoil ionas go nglaictar aon chéim is gá. Is iad na príomh-níthe a bhfuilimid gniomhach leo ná comhsaoil na hÉireann a chosaint agus cinntiú go bhfuil forbairt inbhuanaithe.

Is comhlacht poiblí neamhspleách í an Ghníomhaireacht um Chaomhnú Comhshaoil (EPA) a bunaíodh i mí Iúil 1993 faoin Acht fán nGníomhaireacht um Chaomhnú Comhshaoil 1992. Ó thaobh an Rialtais, is í an Roinn Comhshaoil, Pobal agus Rialtais Áitiúil.

ÁR bhFHÉADRACHTAÍ

CEADÚNÚ

Bíonn ceadúnáis á n-eisiúint againg i gcomhair na níthe seo a leanas chun a chinntiú nach mbíonn astúithe uathu ag cu sláinte an phobail ná an comhsaoil i mbaoil:
- áiseanna drámaíola (m.sh., lionadh talún, loisceoirí, stáisiún aistrithe drámaíola);
- gniomhailochtaí tionscailócha ar scála móir (m.sh., déantaíochtaí cógaisíochta, déantaíochtaí stroighne, stáisiún chumhachta);
- dlíthaimhilochtaí;
- úsáid faoi shráin agus scaulleadh smachtaithe Órgánaí Géinathraithe (GMO);
- mór–áiseanna stórais peitréial; 
- scardadh drámaíoise.

FEIDHMHÍU COMHSHAOIL NÁISIÚNTA

- Stiúradh os cionn 2,000 inúichadh agus cigireacht de áiseanna a fuair ceadúnáis ón nGhníomhaireacht gach bliain.
- Maoirísí freaghrachtai cosanta comhsaoil údaras áitíúla thar sén eamhlí - aer, fuaim, dramhail, dramhuisce agus caighdeán úise.
- Obair le húdarás áitíúla agus leis na Gaoidhchuid chun stop a chur le ghníomhaíocht mhidhleathach drámaíola trí chomhordú agus a dheanann ag lóin forfheidhmhithe náisiúnta, díríú isteach ar chiontóirí, stiúradh fiosrúcháin agus maoirísí leigheas na bhfadhbanna.
- An díol a chur orthu siúd a bhírseann díol chomhsaoil agus a dheanann dochar don chomhsaoil mar thoradh ar a ngníomhaíochtai.

MONATÓIREACHT, ANAILÍS AGUS TUAIRÍSCÍ ÚS AN GCOMHSHAOL

- Monatóireacht ar chaighdeán aer agus caighdeán aibhneach, locha, uiscí taoise agus uiscí talaimh; leibhéal agus sruth aibhneach a thomhas.
- Tuaيرísí neamhspleách chun cabhrú le rialtais náisiúnta agus áitíúla cinntí a dheanamh.

RIALÚ ASUITHE GÁIS CEAPTHA TEASA NA HÉIREANN
- Caintiúchtú astúithe gás ceaptha teasa na hÉireann i gcomhthéacht ar dtómantas Kyotó.
- Cur i bhfeidhm na Treorach um Thrádáil Astúithe, a bhfuil baint aige le hós cionn 100 cuideachta atá ina mór-gheadadóirí dé-oscaid charbóin in Éirinn.

TAIGHDE AGUS FORBAIRT COMHSHAOIL

- Taighde ar saincheisteanna comhsaoil a chomhordú (cosúil le caighdeán aer agus uisce, athrú aeráide, bithéagsúlacht, teicneolaíocht comhsaoil).

MEASÚNÚ STRAITÍISEACH COMHSHAOIL

- Ag déanamh measúnú ar thionchar phleananais agus clárachar ar chomhsaoil na hÉireann (cosúil le pleannanna bainistíochta drámaíola agus forbartha).

PLEANÁIL, OIDEACHAS AGUS TEOIR COMHSHAOIL

- Treoir a thabhairt don phobal agus do thionosc ar cheisteanna comhsaoil éagsúla (m.sh., iarraidh ar cheadúnais, seachaint drámaíola agus rialachán chomhsaoil).
- Eolas níos fearr ar an gcomhsaoil a scaipeadh (tré cláracháil teifísíse chomhsaoil agus pacáistí acmhainne do bhunscoileanna agus do mheánfhothar).

BAINISTÍOCHT DRAMAÍÓLA FHORGHNÍOMHACH

- Cur chun cinn seachaint agus laghdú drámaíola trí chomhordú An Chláir Náisiúnta um Chosc Drámaíola, lena n-áirítear cur i bhfeidhm na dTionscnamh Freagrachta Tairgceirí.
- Cur i bhfeidhm Rialachán ar nós na treoracha maidir le Trealmh Leitreacht agus Leitreoachnaithe seachas drámaíola agus rialachán chomhsaoil.
- Drámaíola a an-áirítear cur i bhfeidhm ar an dtreórachadh a chomhordan d’fhéadfadh í d’fhéadfadh stáisiúin chumhachtaithe a chruthú mar aon duine stuifhinn.
- Pleán Náisiúnta Bainistíochta um Drámaíola Ghaeilge a bhfuil bainistiú drámaíola a chur i bhfeidhm ar an gcomhsaoil.

STRUCHTÚR NA GNÍOMHAIREACHTA

Bunaíodh an Ghníomhaireacht i 1993 chun comhsaoil na hÉireann a chosaint. Tá an eagraíocht a thabhairt don ghníomhaireacht ag Bord Lánaimseartha, ar a bhfuil Príomhthrúthóir agus ceathrú Stiúrthóirí.

Tá an eagraíocht ar Ghníomhaireachta agus ar Ghníomhaireacht na hÉireann a ríomhairte agus ar an gchomh-chumhachtaithe a thabhairt. Tá an eagraíocht ar Ghníomhaireacht na hÉireann a ríomhairte agus ar an gchomh-chumhachtaithe a thabhairt.

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Climate Change Research Programme (CCRP) 2007-2013

The EPA has taken a leading role in the development of the CCRP structure with the co-operation of key state agencies and government departments. The programme is structured according to four linked thematic areas with a strong cross cutting emphasis. Research being carried out ranges from fundamental process studies to the provision of high-level analysis of policy options.

For further information see
www.epa.ie/whatwedo/climate/climatechangeresearch