Report No.401

Peatland Properties Influencing Greenhouse Gas Emissions and Removal

Authors: Florence Renou-Wilson, Kenneth A. Byrne, Raymond Flynn, Alina Premrov, Emily Riondato, Matthew Saunders, Killian Walz and David Wilson

www.epa.ie

Rialtas na hÉireann
Government of Ireland

ENVIRONMENTAL PROTECTION AGENCY

The Environmental Protection Agency (EPA) is responsible for protecting and improving the environment as a valuable asset for the people of Ireland. We are committed to protecting people and the environment from the harmful effects of radiation and pollution.

The work of the EPA can be divided into three main areas:

Regulation: *We implement effective regulation and environmental compliance systems to deliver good environmental outcomes and target those who don't comply.*

Knowledge: *We provide high quality, targeted and timely environmental data, information and assessment to inform decision making at all levels.*

Advocacy: *We work with others to advocate for a clean, productive and well protected environment and for sustainable environmental behaviour.*

Our Responsibilities

Licensing

We regulate the following activities so that they do not endanger human health or harm the environment:

- waste facilities *(e.g. landfills, incinerators, waste transfer stations)*;
- large scale industrial activities (*e.g. pharmaceutical, cement manufacturing, power plants)*;
- intensive agriculture *(e.g. pigs, poultry)*;
- the contained use and controlled release of Genetically Modified Organisms *(GMOs)*;
- sources of ionising radiation *(e.g. x-ray and radiotherapy equipment, industrial sources)*;
- large petrol storage facilities;
- waste water discharges;
- dumping at sea activities.

National Environmental Enforcement

- Conducting an annual programme of audits and inspections of EPA licensed facilities.
- Overseeing local authorities' environmental protection responsibilities.
- Supervising the supply of drinking water by public water suppliers.
- Working with local authorities and other agencies to tackle environmental crime by co-ordinating a national enforcement network, targeting offenders and overseeing remediation.
- Enforcing Regulations such as Waste Electrical and Electronic Equipment (WEEE), Restriction of Hazardous Substances (RoHS) and substances that deplete the ozone layer.
- Prosecuting those who flout environmental law and damage the environment.

Water Management

- Monitoring and reporting on the quality of rivers, lakes, transitional and coastal waters of Ireland and groundwaters; measuring water levels and river flows.
- National coordination and oversight of the Water Framework Directive.
- Monitoring and reporting on Bathing Water Quality.

Monitoring, Analysing and Reporting on the Environment

- Monitoring air quality and implementing the EU Clean Air for Europe (CAFÉ) Directive.
- Independent reporting to inform decision making by national and local government *(e.g. periodic reporting on the State of Ireland's Environment and Indicator Reports)*.

Regulating Ireland's Greenhouse Gas Emissions

- Preparing Ireland's greenhouse gas inventories and projections.
- Implementing the Emissions Trading Directive, for over 100 of the largest producers of carbon dioxide in Ireland.

Environmental Research and Development

- Funding environmental research to identify pressures, inform policy and provide solutions in the areas of climate, water and sustainability.

Strategic Environmental Assessment

- Assessing the impact of proposed plans and programmes on the Irish environment *(e.g. major development plans)*.

Radiological Protection

- Monitoring radiation levels, assessing exposure of people in Ireland to ionising radiation.
- Assisting in developing national plans for emergencies arising from nuclear accidents.
- Monitoring developments abroad relating to nuclear installations and radiological safety.
- Providing, or overseeing the provision of, specialist radiation protection services.

Guidance, Accessible Information and Education

- Providing advice and guidance to industry and the public on environmental and radiological protection topics.
- Providing timely and easily accessible environmental information to encourage public participation in environmental decision-making *(e.g. My Local Environment, Radon Maps)*.
- Advising Government on matters relating to radiological safety and emergency response.
- Developing a National Hazardous Waste Management Plan to prevent and manage hazardous waste.

Awareness Raising and Behavioural Change

- Generating greater environmental awareness and influencing positive behavioural change by supporting businesses, communities and householders to become more resource efficient.
- Promoting radon testing in homes and workplaces and encouraging remediation where necessary.

Management and structure of the EPA

The EPA is managed by a full time Board, consisting of a Director General and five Directors. The work is carried out across five Offices:

- Office of Environmental Sustainability
- Office of Environmental Enforcement
- Office of Evidence and Assessment
- Office of Radiation Protection and Environmental Monitoring
- Office of Communications and Corporate Services

The EPA is assisted by an Advisory Committee of twelve members who meet regularly to discuss issues of concern and provide advice to the Board.

EPA RESEARCH PROGRAMME 2021–2030

Peatland Properties Influencing Greenhouse Gas Emissions and Removal

(AUGER Project)

(2015-CCRP-MS.30)

EPA Research Report

A copy of the end-of-project Technical Report is available on request from the EPA

Prepared for the Environmental Protection Agency

by

University College Dublin

Authors:

Florence Renou-Wilson, Kenneth A. Byrne, Raymond Flynn, Alina Premrov, Emily Riondato, Matthew Saunders, Killian Walz and David Wilson

ENVIRONMENTAL PROTECTION AGENCY
An Ghníomhaireacht um Chaomhnú Comhshaoil
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

ACKNOWLEDGEMENTS

This report is published as part of the EPA Research Programme 2021–2030. The EPA Research Programme is a Government of Ireland initiative funded by the Department of the Environment, Climate and Communications. It is administered by the Environmental Protection Agency, which has the statutory function of co-ordinating and promoting environmental research.

The authors would like to acknowledge the members of the project steering committee, namely Phillip O'Brien (EPA), Dr Bernard Hyde (EPA), Dr Connor Quinlan (EPA), Dr Stuart Green (Teagasc), Professor Eeva-Stiina Tuittila (University of Eastern Finland), Dr Jagadeesh Yeluripati (James Hutton Institute, UK) and Oonagh Monahan (Research Project Manager on behalf of the EPA).

Special thanks go to Dr Jagadeesh Yeluripati from the Information and Computational Sciences Department, James Hutton Institute, Aberdeen, and to Mr Mark Richards and Mr Martin Michael from the Environmental Modelling Group, University of Aberdeen, for the provision of the ECOSSE model and for their great support and advice on using the model. Thanks go to Dr Jason Flanagan, Dr Paul Nolan and Christopher Werner from the Irish Centre for High-End Computing (ICHEC) for their support in accessing the required climate data.

DISCLAIMER

This report is based on research carried out/data from April 2016 to January 2021. More recent data may have become available since the research was completed.

EPA RESEARCH PROGRAMME 2021–2030
Published by the Environmental Protection Agency, Ireland

ISBN: 978-1-80009-026-2 January 2022

Price: Free Online version

Project Partners

Dr Florence Renou-Wilson
UCD School of Biology and Environmental Science
Science West
University College Dublin
Belfield
Dublin 4
Ireland
Email: florence.renou@ucd.ie

Dr Kenneth A. Byrne
Department of Biological Sciences
University of Limerick
Limerick
Ireland
Email: ken.byrne@ul.ie

Dr Raymond Flynn
School of Natural and Built Environment
Queen's University Belfast
Belfast
UK
Email: r.flynn@qub.ac.uk

Dr Matt Saunders
Botany Department
Trinity College Dublin
Dublin 2
Ireland
Email: saundem@tcd.ie

Dr David Wilson
Earthy Matters Environmental Consultants
Glenvar
Co. Donegal
Ireland
Email: david.wilson@earthymatters.ie

Contents

List of Figures

List of Tables

List of Boxes

Executive Summary

A nationwide peatland survey was conducted across 50 ombrotrophic peatlands (bogs) in Ireland to ascertain a wide range of peat properties. In addition to natural (relatively intact) sites, we surveyed the most prevalent peatland land use categories (LUCs): grassland, forestry and peat extraction (both industrial and domestic), as well as management options (deep drained; shallow drained; rewetting). Furthermore, the entirety of the peat profile (down to the sub-peat mineral soil/bedrock) was sampled. Our results demonstrate that Irish bogs have been drastically altered by human activities and that the sampled peat properties reflect the nature and magnitude of the impact of the land use and management.

Natural bogs were found to be the deepest of all LUCs. When the residual peat depths under the other LUCs are compared, a picture emerges of more intensive use of raised and mountain bogs than of lowland blanket bogs. The shallower depths under all LUCs (compared with natural sites) indicate high rates of subsidence and loss of peat through organic matter decomposition, as well as peat removal due to domestic and industrial extraction. Lowland blanket bogs exhibit the least degradation due to their more extensive use.

Using the areal extent of all LUCs reported in the National Inventory Report, we estimate the carbon stock held in natural and managed peatlands in Ireland at 2216 Mt of carbon, with *c.*42% in raised bogs, *c.*42% in lowland blanket bogs and *c.*15% in mountain blanket bogs. Natural and cutover peatlands together contain just under half of the national peatland carbon stock.

Deep-drained grassland was at the extreme end of the degradation scale encountered (compared with natural bogs), containing the lowest organic matter and total organic carbon contents. However, combined with greater bulk density values, this LUC comprises large soil organic carbon densities and contains a valuable carbon stock. Nonetheless, high von Post (humification) and high ash content values indicate that this peatland LUC is very sensitive to continued organic matter decomposition and, thus, this LUC remains a potential hotspot of carbon dioxide (CO_2) and nitrous oxide (N_2O) emissions.

Despite a shallower peat depth, cutover bogs hold the largest soil organic carbon stock ($t\,C\,ha^{-1}$) after natural peatlands regardless of peatland type. These results imply the importance of these degraded ecosystems in providing some critical ecosystem services. Therefore, they should be identified for immediate management interventions to prevent further degradation, particularly the ongoing loss of their carbon store. For instance, the drained cutover bog at Moyarwood in our study was found to emit $5.2\,t\,CO_2\,ha^{-1}\,y^{-1}$ over a 5-year monitoring period. Rewetting at Moyarwood resulted in a sustained and elevated water level and rapidly switched this degraded site into a net sink of $3.8\,t\,CO_2\,ha^{-1}\,y^{-1}$ (5-year average). Moreover, initial results from Clara bog indicate that it is a strong CO_2 sink under “normal” climatic years. Methane emissions remained elevated at Moyarwood for at least 5 years after rewetting. Given the large heterogeneity of peatlands demonstrated in this study, our results indicate that more sites must be monitored for greenhouse gas dynamics across a wider geographical range.

Finally, work carried out on the ECOSSE model using an improved water table simulation approach (i.e. application of a seasonally varying drainage factor) could improve the model’s performance in the simulation of CO_2 fluxes, thus contributing towards potential future development of process-based modelling approaches (Intergovernmental Panel on Climate Change Tier 3 methodology) for estimating and reporting greenhouse gas emissions from peatlands under various LUC/management practices.

Overall, recognition of the heterogeneity found across Irish peat soils, together with an understanding of the relationships between key soil properties, is critical to developing effective strategies for remedial management of these degraded ecosystems. This study and its findings clearly support the need for a site-by-site approach for future rewetting management schemes.

1 Peatlands and Greenhouse Gas Fluxes

1.1 Policy Impetus

The importance of the peatland carbon stock and greenhouse gas (GHG) fluxes in the international framework of climate change mitigation and adaptation has been widely acknowledged. International biodiversity and climate change conventions [Convention on Biological Diversity and United Nations Framework Convention on Climate Change (UNFCCC)] now recognise peatlands as a priority for action, with peatland rewetting and restoration identified as “low-hanging fruit, and among the most cost-effective options for mitigating climate change” [Achim Steiner, United Nations (UN) Under-Secretary-General and Executive Director of the UN Environment Programme].

The introduction of the Wetlands Drainage and Rewetting (WDR) activity under Article 3.4 in the second commitment period of the Kyoto Protocol provided countries with the opportunity to report GHG emissions or removals from drained and rewetted organic soils, respectively, although Ireland did not elect to report this activity. The second Kyoto Protocol period (2013–2020) has concluded, and the first period of the EU Land Use, Land Use Change and Forestry (LULUCF) Regulations under the EU Climate and Energy Framework will run from 2021 to 2025 (the second period is 2026–2030). Ireland has chosen to elect managed wetlands for the first commitment period under these regulations before undertaking mandatory accounting for the second period. The LULUCF Regulations base year is the average value from 2005 to 2009.

At EU level, wetlands have already been highlighted as playing a central role in achieving the temperature goals in the Paris Agreement, and peatlands are already included in the 2030 Climate and Energy Framework [Regulation (EU) 2018/841; European Union, 2018]. At the national level, the Climate Action and Low Carbon Development (Amendment) Bill (2021) provides a legal framework that will “support Ireland’s transition to Net Zero and achieve a climate neutral economy by no later than 2050” (Government of Ireland, 2021). The Government of Ireland plans to introduce a series of strategies that includes “removals” but fails to specify how they will be used in assessing progress towards the targets. Ireland has significant emissions in the LULUCF sector at present, largely due to the management of Irish peatlands, specifically grassland on organic soils. These need to be addressed to achieve the 2050 objective. One contribution to the lowering of emissions should involve improving the management of carbon-rich soils, such as peatlands, as recommended by the Climate Change Advisory Council in its annual review (CCAC, 2020): “The rewetting of drained peatlands is one of the most cost-effective measures supported by carbon tax revenue.” This has been re-affirmed in the European Green Deal, with new Common Agriculture Policy instruments (CAP 2021–2027) currently negotiated to decrease GHG emissions associated with managed peatlands (European Union, 2020). Although the ultimate effect is debatable, offsetting emissions in sectors that are difficult to abate (aviation) has been targeted with international schemes involving peatland restoration (ICAO, 2016). Of significance is the government-funded Peatland Climate Action Scheme (PCAS) to manage 33,000 ha of publicly owned cutaway peatlands, as well as the uncut fringe peatlands, in a way that will safeguard the carbon stored in the remaining peat and contribute to further net carbon sequestration where possible (DECC, 2020).

1.2 Reporting Emissions and Removals

Action to improve the management of peatlands requires a capability to accurately report GHG emissions/removals. The Intergovernmental Panel on Climate Change (IPCC) 2013 Wetlands Supplement (IPCC, 2014) set out methodological guidance for the quantification and accounting of GHG emissions/removals associated with the management of different wetland types. From an Irish perspective, the IPCC Wetlands Supplement provides a rigorous and comprehensive methodological framework for reporting under the LULUCF Regulations. Its implementation is, however, not without issues.

First, the Tier 1 default emission factors may not be transferrable to an Irish situation: Renou-Wilson *et al*. (2014) point to a unique combination of peat soil properties and local management of grasslands over peat soils that affect the emission factors of these land use categories (LUCs); Wilson *et al*. (2015) also identified several site-specific factors (peat quality) that affect the emission factors of extracted/exploited peatlands. In addition, some peatland types may not be well represented, in particular blanket bogs, a dominant component of the Irish peat soils resource. Overall, these discrepancies point towards the need to improve our fundamental understanding of the role of peatland properties in the carbon cycle, with the main uncertainties identified as (1) the carbon density of peat soils, (2) regional peat volumes, (3) nutrient contents and (4) water table levels (WTLs). These gaps have been addressed in the AUGER project (see Box 1.1) through the deployment of a national survey of peat soil properties (Chapter 3).

Second, although it is possible for Ireland to use country-specific emission factors (Tier 2 level), this comes with caveats. The IPCC Fifth Assessment Report has highlighted that a greater density of observations, coupled with sampling strategies appropriate to specific observation types, is required for monitoring hotspot carbon pools/fluxes in large carbon reservoirs, such as peatlands (IPCC, 2013). Although several Irish studies have now contributed to the reporting of GHG emissions from managed peatland LUCs at Tier 2 levels (Wilson *et al*., 2015), the current state of GHG observations is not adequate given the significant hotspots of carbon dioxide (CO_2) represented by a specific LUC, and the contrasting smaller footprint of specific managed peat soils under extensive grassland (Renou-Wilson *et al*., 2016).

Box 1.1. AUGER project objectives

Identifying pressures

Peatlands have played an important role in climate regulation over the past 10,000 years. Natural peatlands are a small carbon sink [absorbing CO_2 while emitting methane (CH_4)] but 80% of Irish peatlands have been damaged to various extents. Anthropogenic disturbances, mainly in the form of drainage (for agriculture and forestry) and peat extraction, result in increased CO_2 and nitrous oxide (N_2O) emissions, and reduced CH_4 emissions. To mitigate emissions from peatlands two actions are required: avoid new or recurrent drainage, and reduce emissions from existing drained areas. To provide better climate policy instruments involving peat soils, basic information on the peatland resource and associated properties are required.

Therefore, the main objective of this project was to carry out a nationwide survey to document the properties of various types of peatlands and peat soils, how they are affected by various management options and how this influences the carbon and GHG dynamics of these systems, thereby quantifying the role of human activities on the climate footprint of Irish peatlands.

The key objectives were to:

1. Characterise peatland types (LUCs) and their associated edaphic and ecosystem properties. This will build on existing data to identify potential gaps to be filled and will be further informed by a nationwide peatland survey of the physical, chemical and ecological properties of peatlands and peat soils (and overall assessment condition). A database that regroups all types of peatlands under existing LUCs (including "natural") and management will be compiled.
2. Support ongoing field observations and modelling of GHG emissions/removals at two core peatland sites, Moyarwood and Clara bog, to improve Tier 2 IPCC reporting.
3. Model anthropogenic impacts on GHG emissions by developing the ECOSSE model to allow Ireland to move to the Tier 3 level of reporting.

Moreover, as Ireland has chosen to elect managed wetlands for the first commitment period under the EU LULUCF Regulations, there is a need to investigate rewetted peat soils in the various LUCs.

The AUGER project set out to fill critical knowledge gaps by monitoring a rewetted and a near-natural peatland to provide much-needed country-specific net ecosystem carbon balances (NECBs) (Chapter 4). At the same time, the capability and potential expansion of an integrated observation network in Ireland was also reviewed (see the end-of-project Technical Report).

Third, given the significant proportion of peat soils, it is in the country's interest to move to higher GHG reporting levels (Tier 3). Process-based models have the potential to integrate the interactions between various carbon pools of the peatland ecosystem, as well as providing improved spatial and temporal estimates of GHG exchange. They do, however, require a very high level of information and complexity with regard to the interactions and processes described above, and require existing observations to support model development, site parameterisation and testing. Many deficiencies have been highlighted, especially in the modelling of simulated soil water, resulting in significant discrepancies in the simulation of CO_2 fluxes relative to the observed data (Flattery *et al*., 2018). The AUGER project set out to review and identify effective biogeochemical process-based models to predict GHG emissions/removals under various management practices (Chapter 5). To contribute towards the future development of Tier 3 methodologies for estimating peatland GHG emissions in Ireland, the focus was then placed on the development of approaches to improve the "Model to Estimate Carbon in Organic Soils – Sequestration and Emissions" (ECOSSE) (Smith *et al*., 2010). It was a particular requirement that these modelling improvements should permit the inclusion of different peatland land use/management categories, such as drainage and rewetting/restoration, in the predictions.

2 Irish Peatlands

2.1 A Unique, Sensitive Resource

In Ireland, peatlands form a substantial part of the physical and cultural landscape. Irish peatlands are predominantly bogs[1] (~1.4 M ha) (Connolly, 2018) with a very small area of fens (~20,000 ha) (NPWS, 2015). The word “bog” is derived from the Gaelic *bogach* and is an internationally accepted word for “ombrotrophic” peatlands, referring to those peatlands that receive all of their water and nutrients from precipitation. Three bog types can be distinguished in Ireland, based on their surface vegetation and genesis (Hammond, 1981). These are raised bogs, lowland blanket bogs and mountain blanket bogs (see Box 2.1). Raised bogs occur in the central part of the island (Midlands) and range from a “true Midland type” to a “transitional Midland type” in the west of the country where precipitation is greater. They originally formed in postglacial lakes that underwent subsequent terrestrialisation. Meanwhile, blanket bogs developed from paludification[2] of the landscape, and both lowland and mountain types extend over either mineral soils or acidic bedrock and quaternary deposits.

While covering *c*.20% of the land surface, much of the peatland area has been extensively modified by human actions. Currently, more than 40% of the peatland area does not possess the original hydrophytic vegetation, which has been replaced by forest or grass or removed altogether through peat extraction for energy, horticulture and domestic purposes (Wilson *et al*., 2013a). Only 20% of the national peatland resource is deemed of conservation value, with intact raised bogs considered one of the rarest habitats in both Ireland and Europe (European Commission, 2017). Many peat soils are under various

Box 2.1. The main types of peatlands found in Ireland (photos: Flo Renou-Wilson)

Low-level Atlantic blanket bog (County Mayo)

Mountain blanket bog (County Sligo)

Raised bog and cutover margins (County Roscommon)

Industrial cutaway peatland (County Offaly)

---

[1] The words “bog” and “peatlands” are used interchangeably in this report.

[2] Paludification is peat accumulation over formerly dry mineral soil.

LUCs, namely grassland, forestry or peat extraction (Table 2.1). Land with peat soils is crucial in the global carbon balance, as it contains soils with a substantial carbon content.

2.2 Peatlands and the Carbon Cycle

The carbon in peatlands is stored in a number of pools (i.e. biomass, litter, peat layer, mineral subsoil and pore water) and each pool has its own dynamics and turnover rates. The peat pool is the main long-term store of carbon, as peat largely consists of organic material with, for Irish peats, an average carbon content of 48% (e.g. Renou-Wilson *et al*., 2008). Global peatlands are estimated to contain more than 600 gigatonnes of carbon (as much as all of the terrestrial vegetation, including forests) despite covering less than 3% of the Earth's surface (Xu *et al*., 2018). The carbon store estimate for Irish peat soils – between 53% and 75% of the total Irish soil organic carbon (SOC) stocks – has been associated with large uncertainties owing to a lack of field data (Renou-Wilson *et al*., 2011). The accumulation of these vast quantities of carbon occurs over many thousands of years and results from the slow accumulation of partly decomposed plant remains (carbon-rich organic material) under the water-saturated, oxygen-depleted conditions that prevail in natural peatlands.

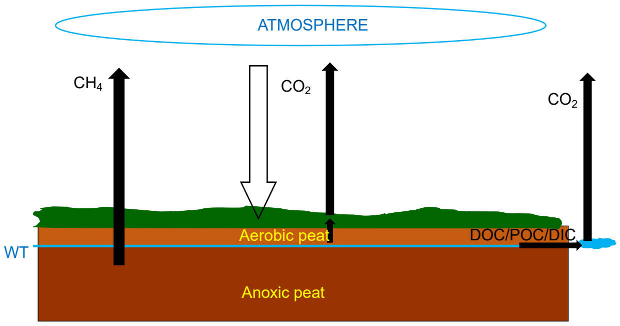
The biogeochemical processes behind this accumulation make natural (undisturbed) peatlands unique ecosystems. In short, they are net sinks for CO_2 and sources of CH_4. Therefore, their climate footprint depends on the magnitude of the land–atmosphere exchange of these two major GHGs (Figure 2.1).

Table 2.1. Estimated areas (ha) of peatland land use categories in Ireland

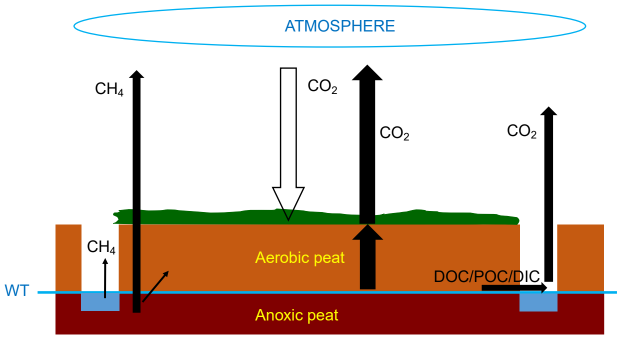
Land use category	Area (ha)	References
Natural	269,267	Wilson *et al.* (2013a)
Forestry	450,940	Duffy *et al.* (2020)
Agriculture		
Grassland	332,000–420,000	Duffy *et al.* (2020), Green (2020)
Cropland	1235	Donlan *et al.* (2016)
Peat extraction		
Industrial	80,000	Duffy *et al.* (2020)
Domestic	101,767–612,000	Malone and O'Connell (2009), Forest Service (2012)
Rewetted	21,000[a]	Wilson *et al.* (2013a)

[a]This figure does not take into account the new Peatland Climate Action Scheme which should see 33,000 ha of industrial peat extraction rewetted between 2021 and 2025.

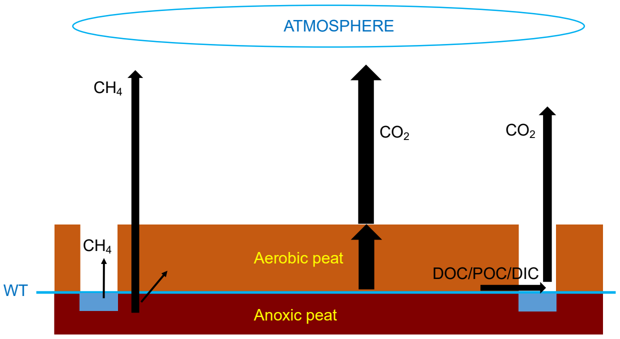
Nitrous oxide (N_2O), on the other hand, becomes significant only in nutrient-rich fens and when wetlands are converted to agriculture or afforested. Globally, wetlands contribute to *c*.20% of total global CH_4



Carbon dynamics in natural peatlands



Carbon dynamics in drained peatlands under grassland/forest/vegetated cutover



Carbon dynamics in extracted peatland

Figure 2.1. Schematic diagrams of gaseous (CO_2, CH_4) and aquatic fluxes in natural, drained and extracted peatlands. DIC, dissolved inorganic carbon; DOC, dissolved organic carbon; POC, particulate organic carbon; WT, water table.

emissions (Saunois *et al*., 2020) and are the main driver of atmospheric CH_4 interannual variations (Bousquet *et al*., 2006). Although the net annual GHG budget of natural peatlands is spatially and temporally variable (McVeigh *et al*., 2014), it is sensitive to natural and anthropogenic perturbations. The climate footprint of peatlands has been found to be strongly dependent on site-specific properties and management (Renou-Wilson *et al*., 2016).

2.3 Factors Influencing Greenhouse Gas Emissions and Removals

2.3.1 Peatland use

The small proportion of natural peatlands that remain in Ireland sequester an estimated $-0.27\,t\,C\,ha^{-1}\,y^{-1}$ (Wilson *et al*., 2013a). However, GHG dynamics are significantly altered when a peatland undergoes a change in land use through human intervention, which generally involves the same fundamental ecosystem changes (i.e. drainage and lowered WTLs), thus producing essentially similar negative effects (Figure 2.1). Increased emissions of CO_2 and N_2O and a reduction in CH_4 emissions have been widely reported for drained grasslands on organic soils (Renou-Wilson *et al*., 2014), for industrially mined peatlands (Wilson *et al*., 2015) and for forested peat soils (Minkkinen *et al*., 2008). Rewetted/restored peatlands have increasingly become the focus of GHG studies, and the effect of rewetting on GHG dynamics in these new ecosystems can be somewhat unpredictable; some studies report high CO_2 and CH_4 emissions post rewetting (Wilson *et al*., 2007, 2009), while other studies have shown that the CO_2 sink function can be re-established relatively quickly (Tuittila *et al*., 1999; Wilson *et al*., 2013b). Peatlands within the Natura 2000 network that have been rewetted and restored are showing promising results, with carbon balances similar to those of natural sites (Regan *et al*., 2020). However, climate change could result in greater CO_2 and CH_4 losses from peatlands, thereby acting as positive feedbacks to climate change (Frolking *et al*., 2011).

Although the emissions/removals from organic soils can occur under any LUC [and is the first disaggregation in the IPCC Wetlands Supplement (IPCC, 2014)], other factors can affect these processes, including the climate (boreal, temperate and tropical) and specific peatland properties. Currently, the “nutrient content” of the peat and “drainage depth” are included in the Tier 1 guidance of the IPCC Wetlands Supplement (IPCC, 2014) as further divisions for reporting the emissions/removals under both drained and rewetted peat soils. Nutrient-poor peat is typically defined as peat that has accumulated in conditions where water and nutrients were received from precipitation only. Nutrient-rich peats, however, also received water (and nutrients) from their surroundings. Furthermore, the delineation between shallow and deep drainage is marked as the mean annual water table either above or below a reference baseline of –30 cm. However, more specific peat properties, coupled with land use management intensity, may affect the decomposition of the organic matter in a synergistic fashion. In all cases of peatland use, where the peat soil is not “wet”, the decomposition of the organic matter, and therefore associated GHG fluxes, are controlled by four main factors that are tightly interrelated:

1. edaphic properties, namely peat carbon and nutrient content;
2. water table position;
3. vegetation/site management;
4. soil temperature regime.

All these processes have been investigated as part of the AUGER project.

3 Peatland Field Investigations

3.1 Background

Organic soils, also referred to as “histosols” or as “peat soils”, are variously defined, depending on the country, scientific discipline or indeed international context (see Box 3.1). In the context of IPCC methodologies, the definition of organic soils is heterogeneous across the EU and is not transparently provided in national GHG inventory reports. In Ireland, organic soils are defined as soils with a high organic matter content (greater than 20%) with a peat depth greater than 30 cm. If the organic or peat layer is less than 30 cm, then the soil is classified as organo-mineral (or peaty-mineral). According to the Irish National Soils Database (Fay *et al*., 2007), the term “organic soils” is used for all soils with an organic carbon content greater than 15% (~25% soil organic matter). Wet organic soils are defined as soils with a water table between 0 and 30 cm below the soil surface. Internationally, wet soils are not defined by the water table but as soils (mineral or organic) that are inundated or saturated by water for all or part of the year to the extent that the biota (particularly soil microbes and rooted plants) has adapted to anaerobic conditions.

3.2 Material and Methods

Several datasets were used to map the area of peat soils in Ireland, to identify geographical clusters that would form primary units for sampling (Figure 3.1). The “Derived Irish Peatland Map” (DIPMV.2) (Connolly and Holden, 2009) and the Irish Soil Information System (Simo *et al*., 2014), along with other available mapping data [CORINE Land Cover 2012 map, Coillte forest cover map, Teagasc EPA Soil Map (Fealy *et al*., 2009)], provided useful additional information for the selection of primary units, sampling sites and plots, as well as sampling locations.

Sampling sites were selected using a multi-stage design (de Gruijter *et al*., 2006), involving the nesting of three sampling levels: 10 primary units were selected within the most representative geographical extent of the three Irish bog types, namely raised bogs, lowland blanket bogs and mountain blanket bogs. These were located in counties Donegal, Galway, Sligo, Mayo, Offaly, Longford and Kerry. Within each primary unit, sampling sites were then selected for each LUC: grassland, forestry, cutover (domestic peat extraction) and cutaway (industrial peat extraction), as well as a natural (near-intact) site. An additional sampling level was introduced to represent the management of the water table, namely drained or rewetted. The definitions follow the IPCC Wetlands Supplement (IPCC, 2014). For grassland, the management level was disaggregated into more refined options: **deep drained** (where the annual water table remains on average –30 cm or deeper below the

Box 3.1. Definition of organic soils

For IPCC methodological purposes (IPCC, 2006, 2014), an organic soil is a soil with a high concentration of organic matter and one that satisfies requirements 1 and 2, or 1 and 3, below:

1. The thickness of the organic horizon is greater than or equal to 10 cm. A horizon of less than 20 cm must have 12% or more organic carbon when mixed to a depth of 20 cm.
2. Soils that are never saturated with water for more than a few days must contain more than 20% organic carbon by weight (i.e. about 35% organic matter).
3. Soils are subject to water saturation episodes and have:
   (a) at least 12% organic carbon by weight (i.e. about 20% organic matter) if the soil has no clay; or
   (b) at least 18% organic carbon by weight (i.e. about 30% organic matter) if the soil has 60% or more clay; or
   (c) an intermediate proportional amount of organic carbon for intermediate amounts of clay.

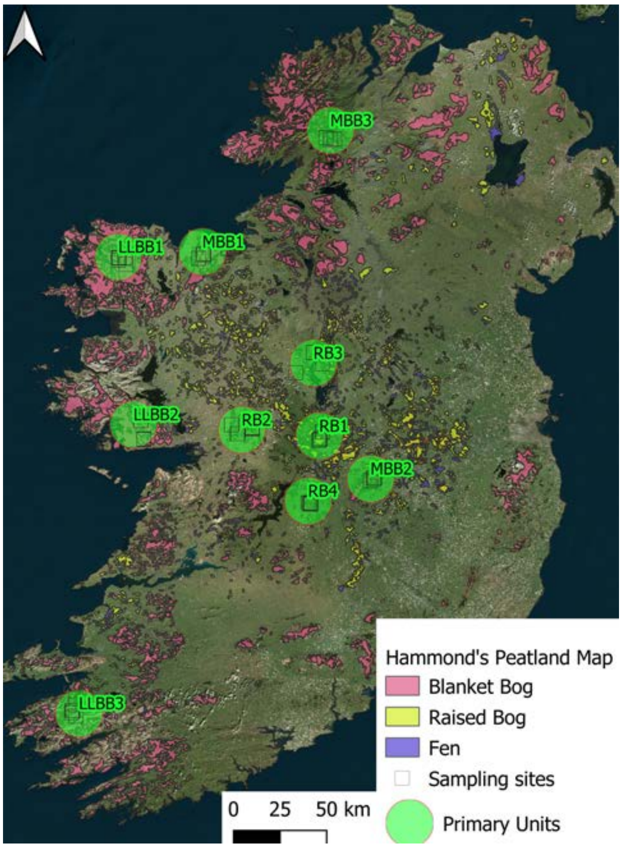


Figure 3.1. Distribution of AUGER sampling sites within primary units (see codes in Table 3.1) in relation to peatlands distribution as per Hammond (1981).

ground level), **shallow drained** (where the annual water table remains on average above –30 cm) and **rough grazing** (containing semi-natural vegetation from bog, heathland or natural grassland habitat, and is used or is suitable for livestock grazing). Some LUCs were not found across all peatland types (e.g. cutaway peatlands in mountain blanket bogs). A total of 50 sites, representing all existing combinations, were sampled (Table 3.1). At each site, sampling locations were randomly chosen, amounting to 270 sampled points (or profiles). At each sampling location, a "Russian" peat sampler (Eijkelkamp, 2005; Pitkänen *et al*., 2011) consisting of a semi-cylindrical steel sample chamber of 500 mm length and a volume of 500 $\mathrm{cm^3}$ was used for extracting soil samples of varying size from consecutive depth intervals along the soil profile (see the end-of-project Technical Report for photographs; they can also be found at https://www.ucd.ie/auger/). The entire depth of the peat soil at each sampling location was sampled into "cores" (0–10 cm; 10–25 cm; 25–50 cm; 50–100 cm; from 100 cm to below the peat–mineral interface layer), until the sub-peat mineral soil or bedrock was reached. A total of 2012 soil aliquots were extracted during the survey.

3.3 Peat Properties Compendium

3.3.1 Main peat properties across peatland types and land use categories

A full database and metadata were compiled for all the peat properties along each profile layer and for each soil aliquot, as well as for each aggregated sample. These included total peat depth, von Post values, dry bulk density (BD; $\mathrm{g\,cm^{-3}}$), pH, electrical conductivity (EC; $\mathrm{mS\,cm^{-1}}$), organic matter content (OM; % dry mass), ash (%), carbon (C; %), nitrogen (N; %), gravimetric water content (WC; g, %) and volumetric water content (WC; % volume), porosity, hydrogen, oxygen and sulfur. A summary of basic statistics is presented in tabular format for the surface peat layer (0–10 cm) in Appendix 1.

Peat depth

The greatest mean depth was encountered in natural raised bogs (6.9 m) (Figure 3.2). For each peatland type, natural bogs were always deeper than other LUCs and the difference was greatest for raised bogs and mountain blanket bogs, demonstrating that these two bog types have been most altered by human activities, while lowland blanket bogs were shown to be more extensively used. Combining all peatland types, the effect of management on peat depth was significant; peat depths under grassland and cutaway were much shallower than those under cutover and forestry management (Figure 3.2). Peat depth is a primary indicator of peat degradation, with drainage leading to both subsidence and loss of volume, as well as loss of peat through organic matter decomposition. In addition, peat extraction reduces the depth of peat. Few, disparate peat depth data sources have been published and used subsequently to estimate SOC. Hammond (1981) reported that the average depth for natural raised bogs was 7.0 m, which corresponds to our results (6.9 m). His average value for cutaways, at 2.5 m, was somewhat greater than the 1.4 m in this study, and confirms the intensification of peat extraction activity. Atlantic lowland blanket bogs, regardless of LUC, were estimated by Hammond at 3.0 m deep, on average (compared with 2.7 m in this study). However, the average depth of mountain blanket bog (1.2 m) compared well with the most

Table 3.1. Nested sampling design with primary unit codes, names (county names in brackets) and number of sites surveyed according to peatland type, land use category and management

		Peatland types										
		Raised bogs				Lowland blanket bogs			Mountain blanket bogs			
		Primary units										
		RB1	RB2	RB3	RB4	LLBB1	LLBB2	LLBB3	MBB1	MBB2	MBB3	
Land use category	Management	Shannonbridge (Offaly)	Woodlawn (Galway)	Longford (Longford)	Birr (Offaly)	Ballycroy (Mayo)	Galway (Galway)	Glencar (Kerry)	Sligo (Sligo)	Slieve Bloom (Offaly)	Donegal (Donegal)	No. sites
Natural	Undrained	Mongan	Monivea	Cloonshanville	Scohaboy	Knockmoyle	Redhill	Ballyghisheen	Letterunshin	The Cut	Croaghonagh	10
Cutover	Drained	Clara	Moyarwood	Castlerea	Scohaboy	Knockmoyle	Redhill	Ballyghisheen	Fiddandary	Glenlahan	Croaghonagh	10
	Rewetted	Moyarwood										1
Cutaway	Drained	Blackwater	Clough	Curraghroe	Ballycollin	Bellacorick						5
	Rewetted	Blackwater				Bellacorick						2
Forestry	Drained	Blackwater	Moyarwood[a]	Mote	Scohaboy	Knockmoyle	Cloosh	Glencanane	Ox Mountains	Glenlahan	Croaghonagh	10
	Rewetted	Scohaboy				Ballyghisheen						2
Grassland	Deep drained (> 30 cm)	Boora		Lanesborough	Scohaboy	Knockmoyle		Gortnagan				5
	Shallow drained		Moyarwood									1
	Naturally rewetted (< 30 cm)											
	Rough grazing						Caher	Caanknoogheda	Letterunshin		Croaghonagh	4
Total												**50**

[a] Afforested cutover.

LLBB, lowland blanket bog; MBB, mountain blanket bog; RB, raised bog.

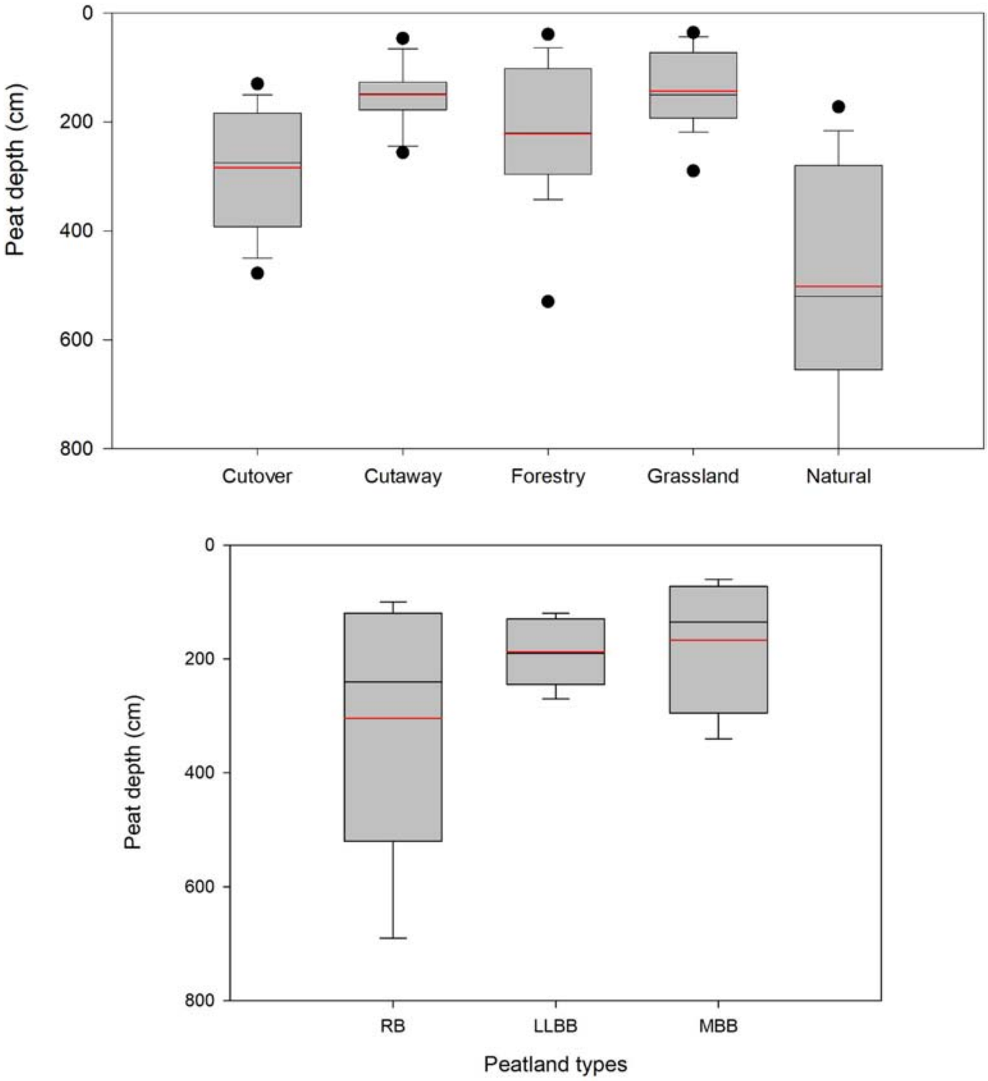


Figure 3.2. Box plot distribution of peat depth (cm) with median (black line) and mean (red line), minimum and maximum values, error bars and outliers (dots), by (top) land use category and (bottom) peatland type. LLBB, lowland blanket bog; MBB, mountain blanket bog; RB, raised bog.

degraded types (grassland and cutover bog) but was much lower than the natural mountain blanket bogs measured in this study (3.4 m). This may be an artefact of the range of elevations where these bogs are found. While it was noted that mountain blanket bogs were more rocky in the west of Ireland than in the east (Wicklow Mountains) and Midlands (Slieve Bloom Mountains), leading to an arbitrary reduction by one-half of the estimated peat depth in Tomlinson's (2005) study, for example, this assumption was not corroborated in our study.

pH

In raised bogs, the mean pH of the surface peat (0–0.1 m depth) in forestry (4.4) and cutover (4.2) was similar to that in natural sites (4.2) (see Appendix 1, Table A1.2). In contrast, the mean pH of the surface peat in grassland (5.9) and cutaway (5.3) was much greater. The mean pH of the surface peat in lowland blanket bog across all land uses was similar to that in their natural equivalent (see Appendix 1, Table A1.2). In mountain blanket bog, the mean pH of the surface peat under forestry (4.9) and grassland (4.8) was greater than in the natural category (3.9).

In general, pH values increased with depth across all site types (Figure 3.3). Deep-drained grassland on both raised bog and lowland blanket bog exhibited greater pH values than shallow-drained grassland. A wider range of peat pH values was observed in peatland sites under forestry and grassland than in their natural equivalent.

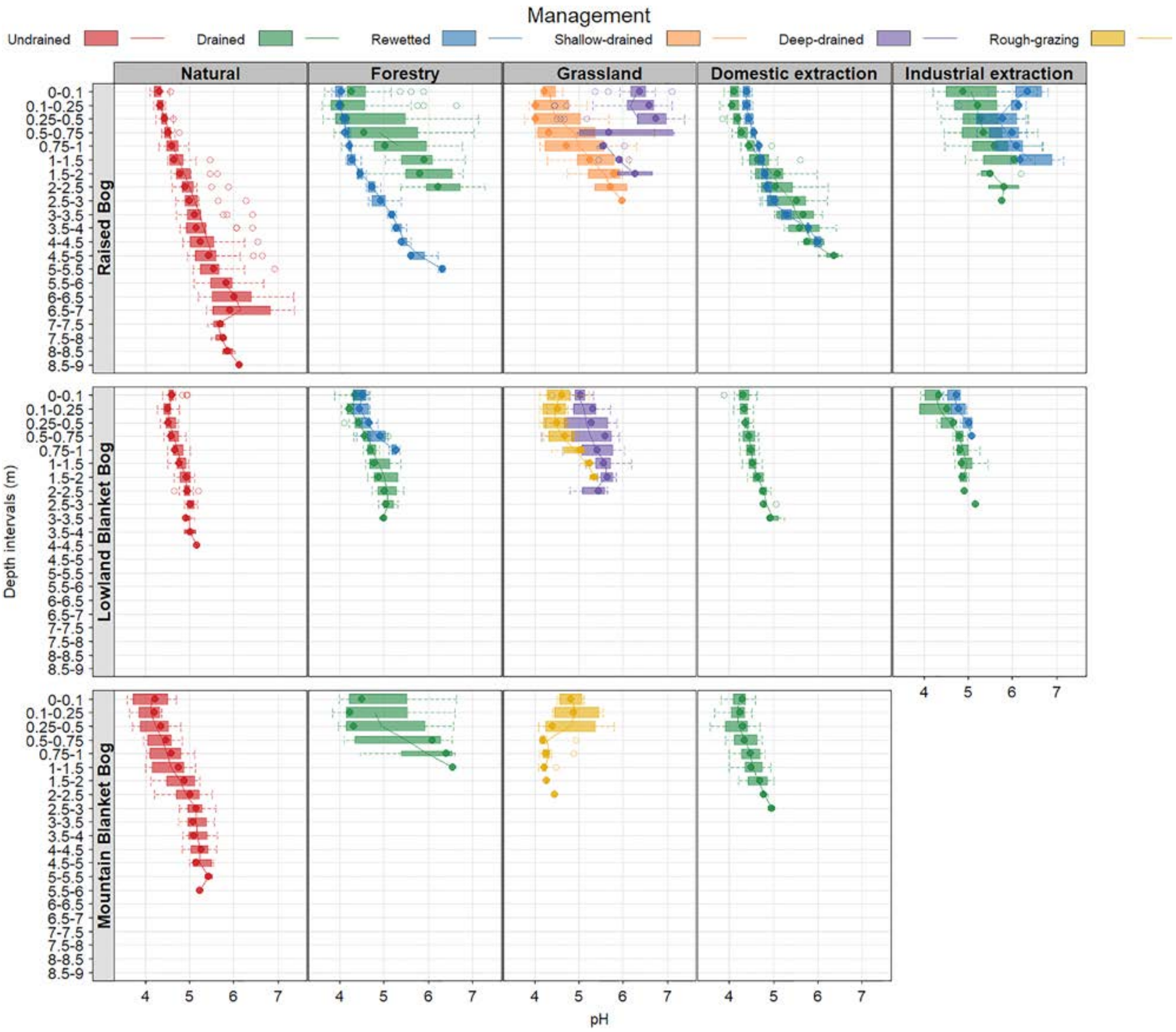


Figure 3.3. Distribution of pH values along the depth gradient for combinations of peatland type (raised bog, lowland blanket bog, mountain blanket bog) and land use category [natural, forestry, grassland, cutover (domestic extraction) and cutaway (industrial extraction)]. Depth intervals (m) are connected through an average line. Colour box plots with error bars depict each peatland type–land use category combination across management options (undrained, drained, rewetted, shallow drained, deep drained, and rough grazing only for grassland).

Bulk density

Bulk density is a very useful indicator of soil degradation, and it can be expected to increase following drainage and subsidence. In both raised bogs and lowland blanket bogs, the mean and median bulk density values of surface peat (0–0.1 m) were greater in all LUCs than in the natural category, with the greatest values observed under grassland (Appendix 1, Table A1.3). In mountain blanket bog, the mean bulk densities in the surface peat were not significantly different between natural peat (0.06 g cm^{-3}) and grassland (0.09 g cm^{-3}), with the greatest mean bulk densities recorded under forestry (0.17 g cm^{-3}). There was little variation in bulk density with depth in all categories, although it was less under rewetted forestry and domestic extraction (raised bog) (Figure 3.4).

The greater bulk density values recorded in deep-drained grassland sites than in shallow-drained grassland sites on both raised bog and lowland blanket peat are evident only at the 0.25 m depth (Figure 3.4).

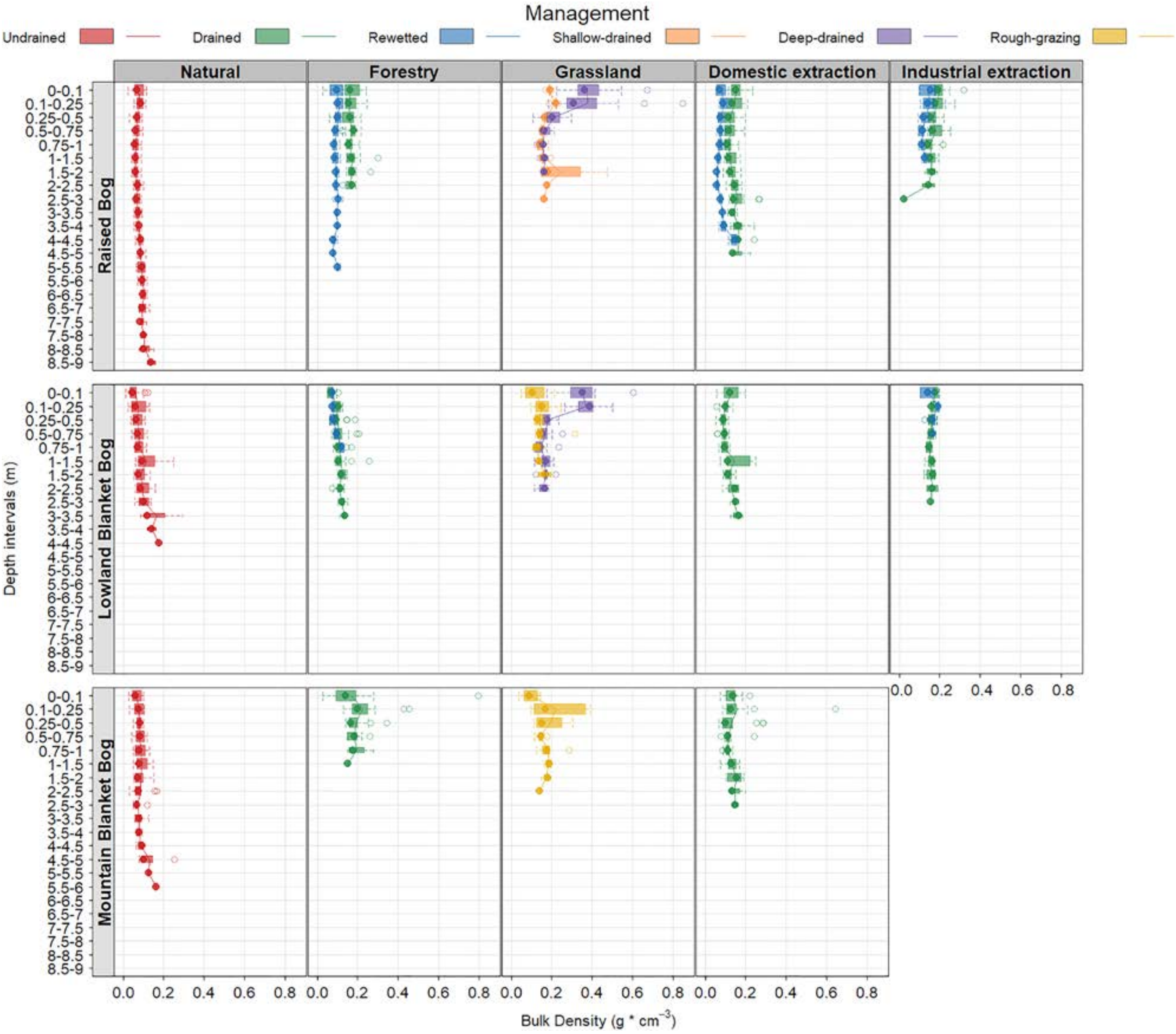


Figure 3.4. Distribution of dry bulk density (g cm^{-3}) values along the depth gradient for combinations of peatland type (raised bog, lowland blanket bog, mountain blanket bog) and land use category [natural, forestry, grassland, cutover (domestic extraction) and cutaway (industrial extraction)]. Depth intervals (m) are connected through an average line. Colour box plots with error bars depict each peatland type–land use category combination across management options (undrained, drained, rewetted, shallow drained, deep drained, and rough grazing only for grassland).

Organic matter

Mean organic matter content of the surface peat (0–0.1 m) was lower in all LUCs, across all peatland types, than in the natural category (Appendix 1, Table A1.4). The lowest mean values were 71.65% in raised bog under grassland and 72.84% in mountain blanket bog under forestry. Organic matter content values showed little change with depth in natural raised bog, lowland blanket bog and mountain blanket bog, except for a slight decrease in the deepest layers in lowland blanket bogs (Figure 3.5). Forestry and grassland exhibited a wider range of values at all depths, with deep-drained grassland in both raised bog and lowland blanket bog displaying lower organic matter values than shallow-drained grassland (Figure 3.5).

Total organic carbon content

In raised bogs, the mean total organic carbon (TOC) content of the surface peat (0–0.1 m) was greater in all LUCs than in the natural category, except for grassland, where it was lower (40.64% vs 51.59%)

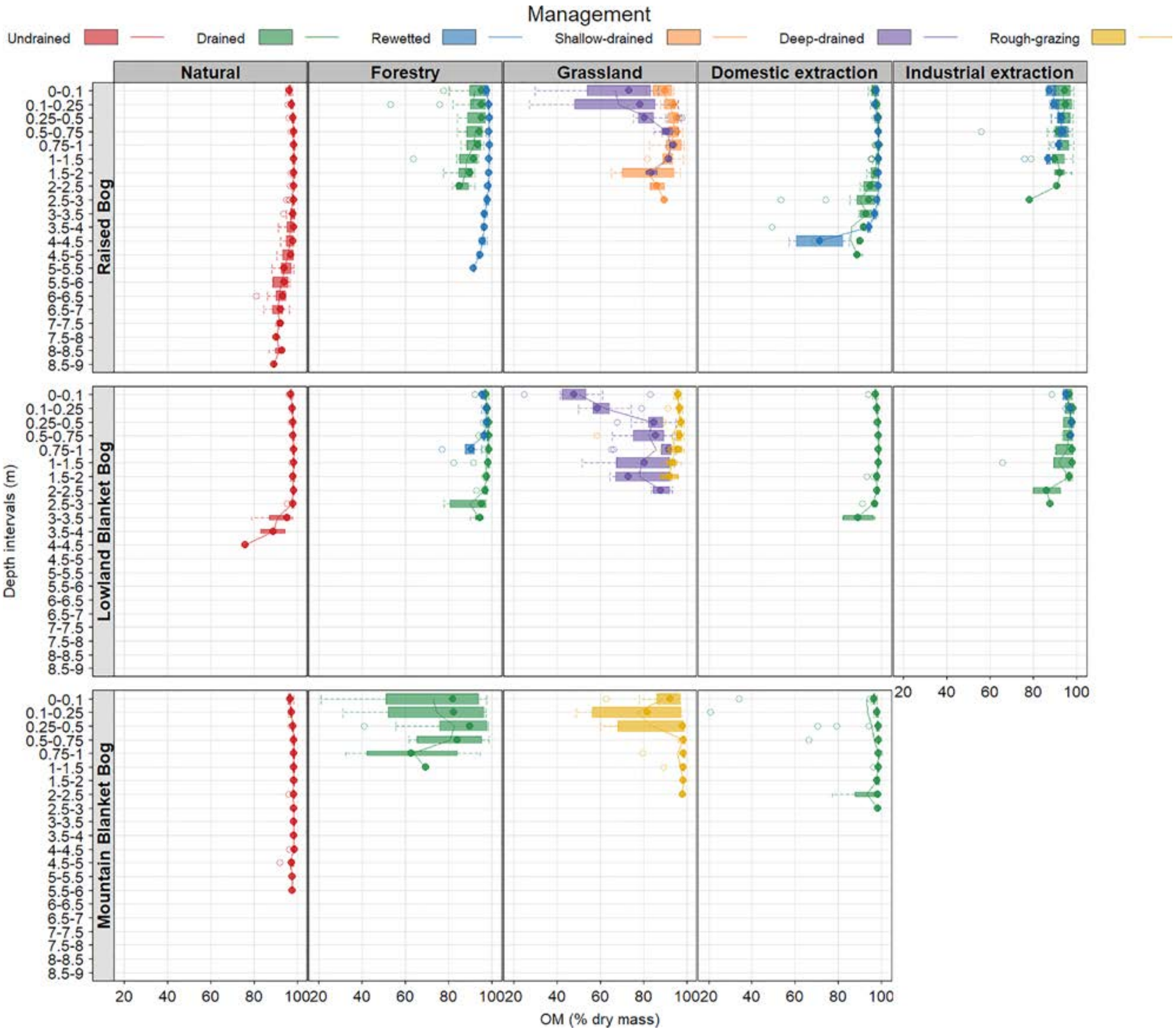


Figure 3.5. Distribution of organic matter values along the depth gradient for combinations of peatland type (raised bog, lowland blanket bog, mountain blanket bog) and land use category [natural, forestry, grassland, cutover (domestic extraction) and cutaway (industrial extraction)]. Depth intervals (m) are connected through an average line. Colour box plots with error bars depict each peatland type–land use category combination across management options (undrained, drained, rewetted, shallow drained, deep drained, and rough grazing only for grassland).

(Appendix 1, Table A1.5). The same pattern was repeated in lowland blanket bog, where the greatest mean TOC value was recorded in the cutaway peatlands. In mountain blanket bog, the mean carbon content of the surface peat (0–0.1 m) was lower in both forestry (39.74%) and grassland (46.77%) than in the natural category (52.79%). Change in TOC content with depth was most evident in deep-drained grassland in both raised bog and lowland blanket bog categories; here a much lower TOC content was observed in the upper 0.5 m of the profile than at greater soil depths (Appendix 2, Figure A2.1).

Nitrogen

Mean nitrogen values in the surface peat (0–0.1 m) of natural bogs were similar in all LUCs except grassland, in which consistently higher nitrogen concentrations were found (Appendix 1, Table A1.6). Depth is a significant covariate of nitrogen concentrations; thus, all "cut" or "subsided" bogs in which the original depth has been affected present a different profile due to the type of peat layer currently at the surface (Appendix 2, Figure A2.2). Significantly, rewetted bogs exhibited higher nitrogen contents than their natural counterparts, with the exception of previously afforested raised bogs and previously cutaway lowland blanket bogs; however, these results are based on very few sites. Overall, nitrogen concentrations across all sampled bogs had a median value of 2.05% (minimum: 1.07%; maximum: 4.03%). Although the distribution is slightly right-skewed by a few high concentration values, this is still greater than the average value for north-western Europe (1.6 ± 0.4%) provided by Loisel *et al*. (2014) and is a reflection of the historical use of Irish peatlands.

3.3.2 Relationships between properties

The soil properties of the peat soils encountered throughout Ireland in this survey were found to vary over a wide range, thereby confirming the pronounced diversity of peat types that are produced under unique conditions at individual sites. Their use and management have also altered peat properties on a very broad scale ranging from acute to limited changes, compared with their "natural" counterparts. The variations encountered reflect the nature and magnitude of the impacts on peatlands and, thus, are critical for developing effective strategies for remedial management of degraded peat systems. Regardless of peatland type, the greatest variations were encountered in the grassland LUC, either vertically (down the peat profile) or horizontally (across the site). This confirms the historical development of grassland on the margins of bogs, where drainage conditions could be improved easily, or where a favourable soil moisture content prevailed post peat extraction.

After drainage (regardless of use), changes in the physicochemical properties of peat occur because of aeration, compaction and increased ash content. The bulk density values were greater in the upper than the lower layers of all LUCs but particularly under grassland, which coincided with greater decomposition (von Post) and pH values (Figure 3.6).

In general, managed peat is characterised by shallower peat depths, higher bulk density and lower carbon values than natural peat. This is particularly the case for deep-drained grassland peat soils. Mountain blanket bogs were the most severely affected by both grassland and forestry, displaying low organic matter content and high bulk density values (Figure 3.7). Cutover bogs differ from natural sites with regard to bulk density values (regardless of peatland type) but exhibit a similar organic matter content. A bulk density value of approximately 0.2 g cm^{-3} was identified as a critical threshold point; above and below this value, macro-porosity and hydraulic parameters follow different pedo-transfer functions with regard to bulk density (Liu and Lennartz, 2019). Across all bogs

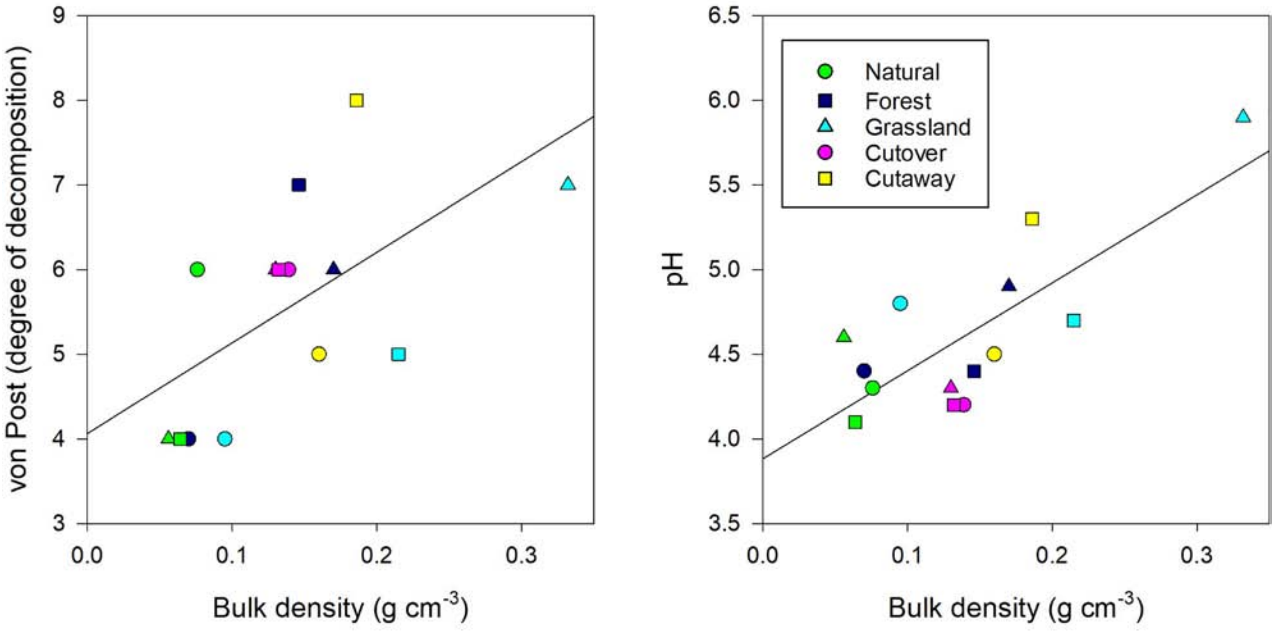


Figure 3.6. Relationship between bulk density (g cm^{-3}) and (left) von Post degree of decomposition (regression line, $r^2 = 0.37$) and (right) pH (regression line, $r^2 = 0.59$) by land use category and peatland type (raised bog, circles; lowland blanket bog, squares; mountain blanket bog, triangles).

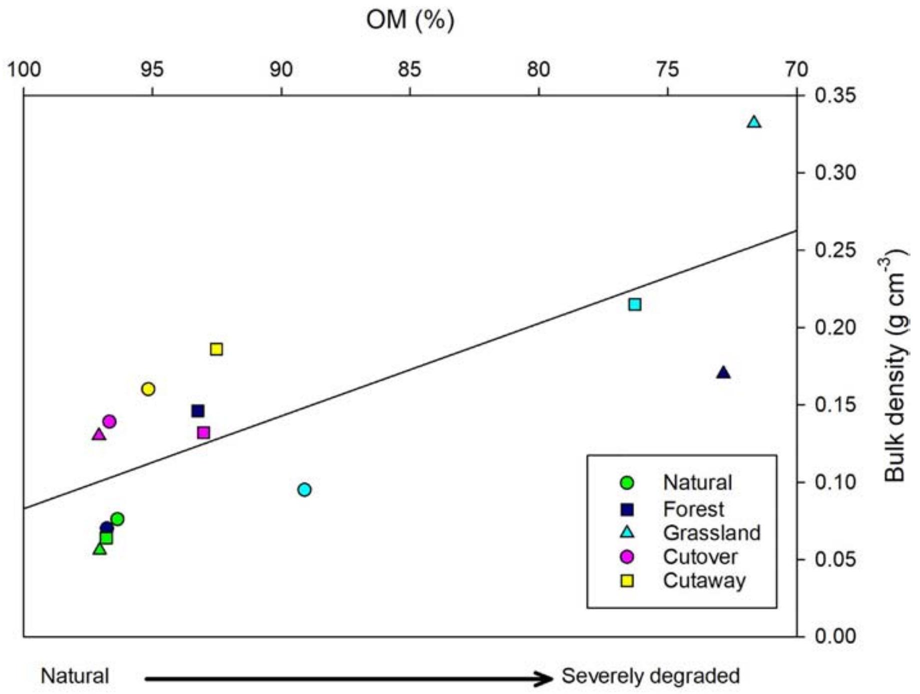


Figure 3.7. Relationship between organic matter and bulk density by land use category and peatland type (raised bog, circles; lowland blanket bog, squares; mountain blanket bog, triangles) and the associated degradation scale. Regression line, $r^2 = 0.59$. Note that the organic matter axis increases from left to right.

and peat depths, the OM/SOC (organic matter/soil organic carbon) ratio was 1.59 (0.20). Such a low conversion factor means that previous estimations of SOC stocks were likely under-estimated.

3.4 Peatland Carbon Stocks and Uncertainties

3.4.1 Soil organic carbon density

While raised bogs exhibited the most variable SOC densities and also had the greatest values, a change of land use affected SOC densities more than peatland type (Figure 3.8). Grassland SOC densities were the most variable and differed significantly from cutover and forestry but not from cutaway. SOC densities increased with land use intensity: natural < cutover < forestry < cutaway < grassland.

3.4.2 Soil organic carbon stock and land use categories

Accurate estimation of SOC stocks is vital to understanding the links between atmospheric and terrestrial carbon. To our knowledge, this is the first time in Ireland that SOC stocks can be derived from actual measured carbon content and bulk density values across the whole peat profile. Initial results demonstrate that natural peatlands comprise large carbon stocks per hectare (or carbon densities), especially raised bogs (3037 t C ha^{-1}) (Table 3.2 and Figure 3.9). Cutover raised bogs contain 80% of the carbon contained in natural peatlands, thereby demonstrating their relative importance in the national carbon stock (Figure 3.9). Cutaway carbon density was 40% of that in natural peatlands. Natural mountain blanket bogs had a greater carbon density (1800 t C ha^{-1}) than lowland blanket bogs (1409 t C ha^{-1}). However, this was reversed for all LUCs associated with blanket bogs. The mountain blanket bog forestry category had the lowest carbon density (476 t C ha^{-1}) but it was more than tripled for lowland blanket bog forestry (1646 t C ha^{-1}).

Grassland had the lowest average carbon density across bog types but displayed the largest standard errors. The values are still larger than previous estimates, including a recent individual ombrotrophic peat soil, which accounted for 748 t C ha^{-1} but was on the shallow end of the spectrum (116 cm) (Tuohy *et al.*, 2021). Overall, the carbon stock decreased as land use intensity increased: natural > cutover > forestry > cutaway > grassland.

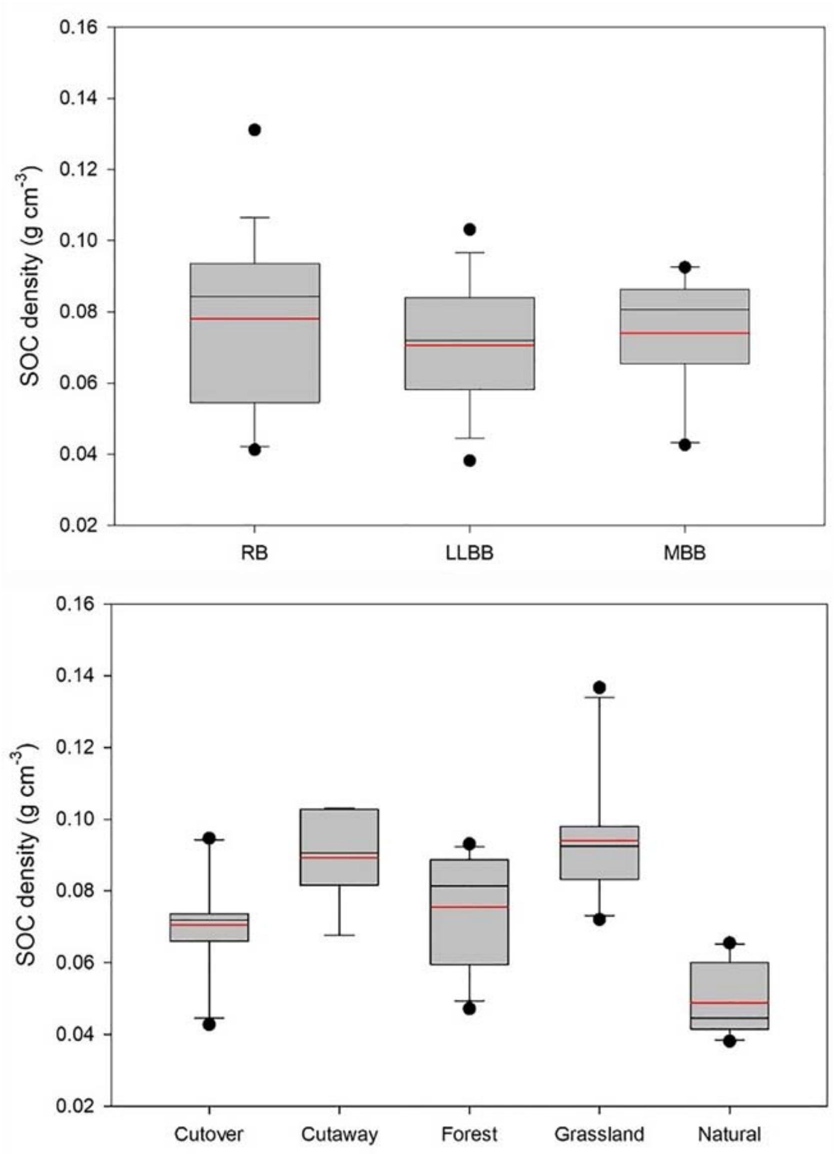


Figure 3.8. Box plot [minimum, maximum, median (black line) and outliers] with mean (red line) soil organic carbon density (g C cm^{-3}), across (top) peatland types (LLBB, lowland blanket bog; MBB, mountain blanket bog; RB, raised bog) and (bottom) LUC.

Table 3.2. Soil organic carbon stock (t C ha^{-1}) by land use category and peatland type with 95% confidence interval in brackets

	SOC stock (t C ha^{-1}) by peatland type		
Land use category	**Raised bog**	**Lowland blanket bog**	**Mountain blanket bog**
Cutover	2398 (9.4)	1550 (11.8)	1248 (16.7)
Cutaway	1240 (13.9)	1396 (10.3)	–
Forestry	1902 (13.2)	1646 (10.7)	476 (15.7)
Grassland	1239 (13.4)	1323 (27.9)	1091 (24.0)
Natural	3037 (8)	1409 (10.6)	1800 (19.1)

–, there is no commercial peat extraction from mountain blanket bogs.

Regardless of LUC, raised bogs contained the largest carbon densities followed by lowland blanket bogs. Mountain blanket bogs displayed the largest variation across sites and LUCs (Table 3.2). When compared with previous estimates of carbon densities for natural and exploited peatland types, it is apparent that peat depth was the critical factor leading to underestimation for the mountain blanket bog category (Eaton *et al.*, 2008). The carbon density estimates for cutaway peatlands were the most comparable, demonstrating the importance of the large datasets already acquired for this LUC.

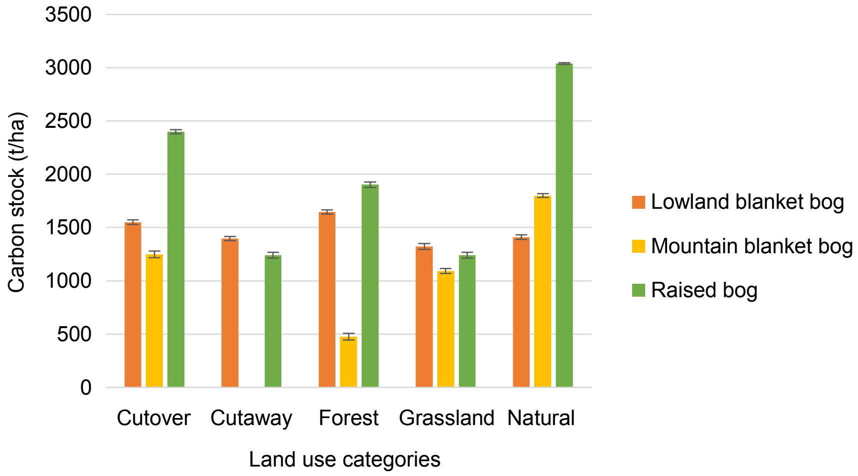


Figure 3.9. Distribution of carbon stock (t ha^{-1}) by peatland type and land use category. Error bars show the 95% confidence interval.

3.4.3 Estimates of national peatland carbon stock

Best areal estimates for each peatland LUC were compiled using various updated sources.[3] The cutover bog areas, to date not measured, were subtracted from the total area of peat soils of 1.454 M ha according to the DIPMV.2 map (Connolly and Holden, 2009). Although the LUC of blanket bogs in general can be estimated reasonably accurately, the disaggregation between mountain and lowland blanket bogs for each LUC has never been determined. The proportion of each bog type found in the DIPMV.2 map (65% lowland blanket bog to 35% mountain blanket bog) was applied.

To our knowledge, this is the first time in Ireland that upscaled carbon stocks have been calculated for each LUC and peatland type, based on total carbon density for the whole peat profile (Table 3.3). Overall, Irish peatlands are estimated to store 2216 Mt of carbon (uncertainty range: 2005–2320). An approximately equal proportion (42%) of the carbon store is located in the raised bogs and lowland blanket bogs, with the remainder (15%) in mountain blanket bogs (Figure 3.10).

Table 3.3. Estimated area (ha) and total carbon stock (Mt) by peatland type and land use category

		Land use category					
Peatland type		**Natural**	**Grassland**	**Forestry**	**Cutaway**	**Cutover**	**Total**
Raised bog	Area (ha)	80,000	171,572	83,000	71,401	98,504	504,477
	C stock (Mt C)	243.0	212.6	157.9	88.5	236.2	938.2
Lowland blanket bog	Area (ha)	123,026	161,478	239,161	8599	96,041	628,305
	C stock (Mt C)	173.3	213.6	393.7	12.0	148.9	941.5
Mountain blanket bog	Area (ha)	66,245	86,950	128,779	–	51,714	333,688
	C stock (Mt C)	119.2	94.9	58.0	0.0	64.5	336.6
Total	Area (ha)	269,270	420,000	450,940	80,000	246,259	1,466,469
	C Stock (Mt C)	535.5	521.1	609.5	100.5	449.6	2,216.3
	Uncertainty range (Mt C)	514–545	444–572	548–632	86–115	413–457	2005–2320

–, denotes no industrial extraction on mountain blanket bogs.

---

[3] NPWS (2016) and M. Eakin, NPWS, personal communication, 2020; M. McCorry, Bord na Móna, personal communication, 2020; DAFM (Duffy *et al*., 2020); EPA (Duffy *et al*., 2020); Teagasc (Green, 2020).

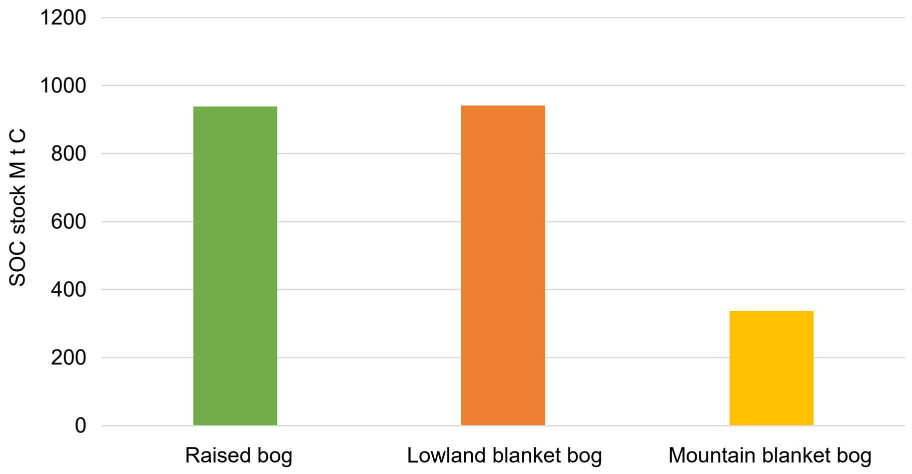


Figure 3.10. Total amount of soil organic carbon (SOC) stock (i.e. carbon stored) (Mt) in each peatland type.

3.5 Water Table Level Monitoring

3.5.1 *Two-year water table level monitoring at a raised and lowland blanket bog*

WTL monitoring was conducted over a 2-year period (November 2017–December 2019) at two peatlands, namely Scohaboy raised bog (RB4, Co. Offaly) and Knockmoyle lowland blanket bog (LLBB1, Co. Mayo). Four LUCs were represented at each site: natural, forestry, cutover and rewetted in Scohaboy, and natural, forestry, grassland and cutover in Knockmoyle.

During the study period, the water table regimes varied significantly between the LUCs at each peatland type (Figure 3.11). The deepest WTLs were recorded in cutover and forestry sites over raised bog in County Offaly (–60.8 cm and –62.2 cm, respectively) compared with natural (–8.0 cm) and rewetted sites (–8.2 cm). The natural lowland blanket bog in County Mayo had a mean WTL of –3.3 cm, with cutover and grassland sites exhibiting similar means (–22.2 and –23.6 cm, respectively), and forestry had the deepest WTL (–33.7 cm). Water retention curves showed that the

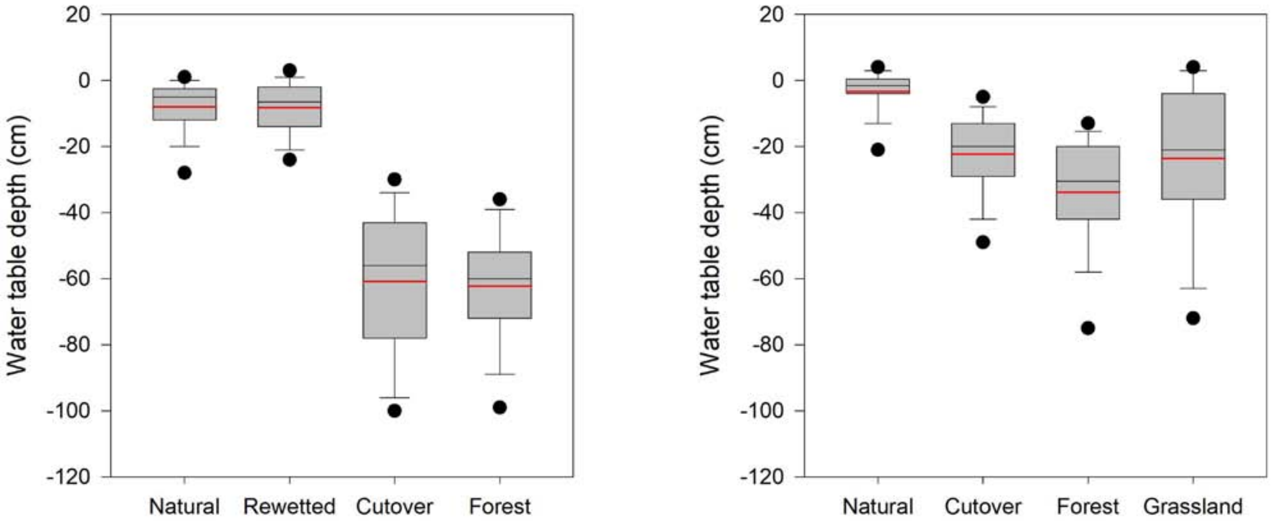


Figure 3.11. Box-and-whisker plots of the water table level mean (red line), median (black line) and outliers (for the 2-year monitoring period 2018–2020) at (left) Scohaboy raised bog and (right) Knockmoyle lowland blanket bog across all land use categories.

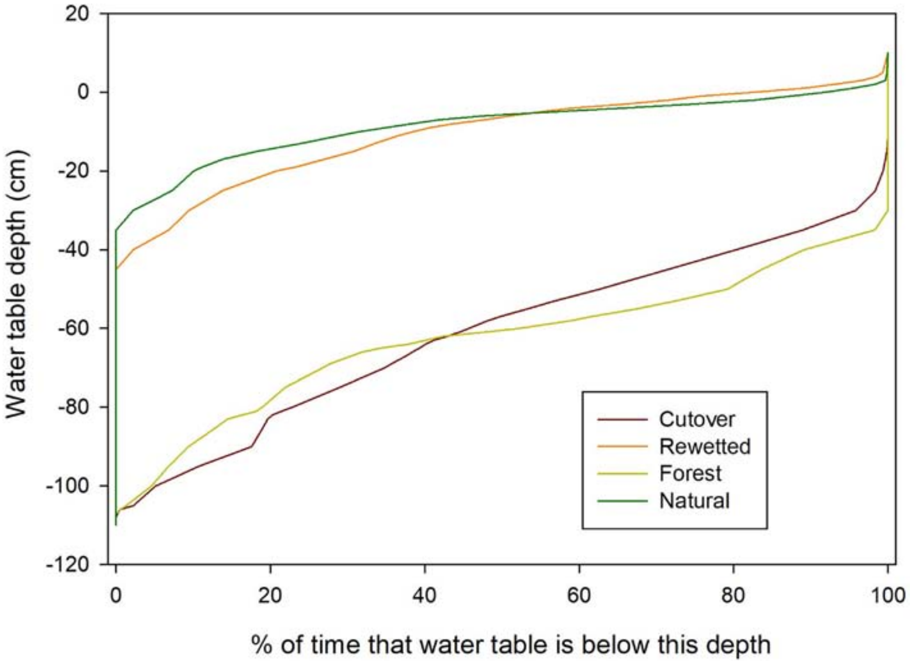


Figure 3.12. Water table level (cm)–residence time curves for each land use category in Scohaboy raised bog (2018–2019).

WTL position remained above –10 cm for 70% of the time in the natural sites, but this decreased to 60% in the rewetted sites (Figure 3.12). At the lowland blanket bog, the natural site was wetter, with the WTL position remaining above –10 cm for 90% of the time. For all other LUCs, the WTL was below –30 cm for more than 50% of the time, with the forestry LUC exhibiting the deepest WTL (Figure 3.13). Seasonal variation was evident, with a summer dip in WTL in all peatlands, which was more substantial in the grassland and

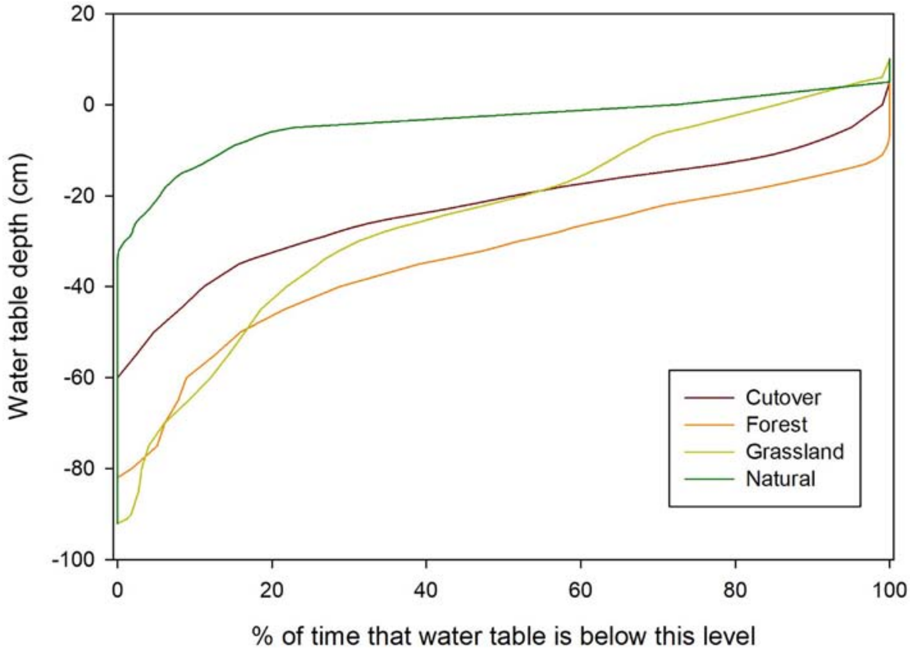


Figure 3.13. Water table level (cm)–residence time curves for each land use category in Knockmoyle lowland blanket bog (2018–2019).

forestry LUCs at Knockmoyle. The cutover LUC demonstrated very erratic WTL regimes at both LUCs, being strongly coupled with precipitation rather than vegetation cover (see the graphics in section 3.5 in the end-of-project Technical Report).

All LUCs demonstrated a wide variation in WTL, irrespective of peatland type, although the erratic regimes were more pronounced in the raised bogs. It should be noted that all sites were relatively flat and thus slopes did not affect the hydrological regimes. In the natural lowland blanket bog, the WTL was less than 10 cm of the ground surface for over 90% of the time, reflecting the negligible supplementary storage capacity available for most of the hydrological year. This dropped to 70% in the natural raised bogs. All of the other LUCs demonstrated greater intra- and interannual fluctuations, with significantly deeper depths of WTL observed in the forestry category, especially in raised bogs. Seasonal variation in WTL was evident in the grassland sites in the west, which highlights the importance of precipitation. Groundwater levels also responded rapidly to rainfall in the cutover sites. The increase in WTL in these sites generally results in increased runoff with associated dissolved organic carbon (DOC).

This study also supports previous work demonstrating success in bringing the WTLs in rewetted bogs back to levels similar to those of their natural counterparts (Renou-Wilson *et al*., 2018). The successful “plumbing” of degraded bogs is the first critical step towards full recovery of the ecosystem, including vegetation. Overall, while monitoring of WTLs in natural/rewetted sites can be successfully achieved by a single logger, the spatial heterogeneity present in the other LUCs warrants the deployment of several loggers.

3.5.2 Water table level monitoring at Moyarwood rewetted site

The hydrological investigations carried out at the rewetted raised bog site at Moyarwood, County Galway (see Chapter 4), aimed to evaluate whether rewetting measures undertaken at the site had succeeded in restoring the hydrological supporting conditions necessary for the re-establishment of peat-accumulating plant communities. The results, once again, revealed a close relationship between WTLs and meteorological data (Figure 3.14). This is particularly apparent when the cumulative deficit (rainfall minus potential evapotranspiration) is compared with WTL fluctuations, with the gradual decline in WTL at the start of the monitoring period and its gradual rise at the end effectively explained by the sensitivity of bog hydrology to meteorological inputs.

The results reveal an intimate relationship between groundwater and drain water levels. The blockage of these drains has resulted in raised water levels. The data collected suggest that this has increased the water level in the surrounding peat, thus reducing the depth to the water table, compared with pre-rewetting conditions. The resulting range in water level falls within that observed in peat-accumulating (central) ecotopes on other Irish bogs (Cushnan, 2018). Consequently, the rewetting measures undertaken are considered to have successfully restored hydrological supporting conditions for peat-accumulating plant communities at Moyarwood. Critically, the success of these measures depends on peat properties, with the deeper peat at the site displaying considerably lower permeability than that encountered at the surface. In cases where peat proves permeable and hydraulic gradients can be controlled, the effects of restoration measures can be anticipated to be more widespread. Conversely, where this control cannot be implemented, restoration measures in permeable peat units are likely to prove less effective, particularly where water levels in adjacent drains drop more than 15 cm below ground level. It should be cautioned that permeability is not a function of current peat depth. Well-humified (high von Post values) peat layers that can limit water fluxes can be present in shallow deposits (e.g. cutaway). However, the near-surface layer of bare peat is likely to have been affected in turn by the absence of vegetation and weathering processes that affect macroporosity and matrix flow.

3.5.3 Water table level monitoring: conclusions

Our results confirm the high variability in hydrological regimes in all peatland types, including natural bogs, whereby different ontogenic development, peat properties (bulk density, degree of decomposition) and allogenic factors (e.g. local climate) will produce

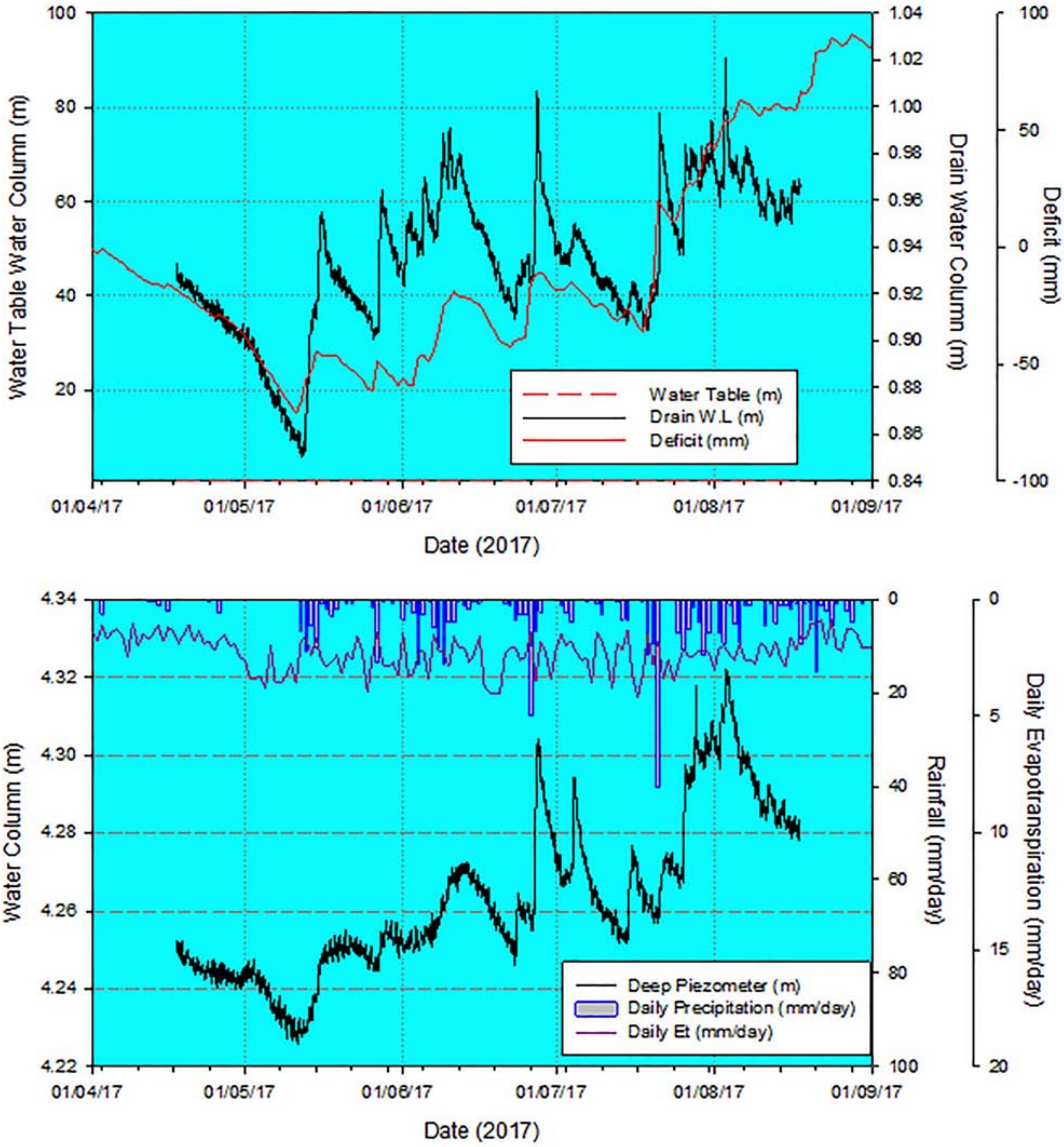


Figure 3.14. Plot of water table level (WTL) fluctuations with meteorological inputs for water table (upper graph) and deep piezometers (lower graph) at Moyarwood, County Galway (April 2017 to August 2017). The meteorological data are from the nearby Met Éireann station at Athenry. Et, evapotranspiration; W.L., water level.

contrasting hydrological regimes both *within* and *between* sites. These relationships become even more complex in drained peatlands. This makes monitoring of this spatiotemporal variable that critically drives GHG dynamics very difficult and would require the deployment of intensive instrumentation at the site.

Although the WTL can be measured reliably in the field using piezometers and shallow monitoring wells, these point-based techniques are difficult to scale. Recent developments using Earth observation data acquired from unmanned aerial vehicles (UAVs) have provided accurate models of groundwater levels, especially in open, treeless peatlands (Rahman *et al*., 2017). This study also supports previous research that confirmed the importance of the relationship between WTL and peat properties when rewetting peatlands, to inform sustainable engineering solutions on a site-by-site basis.

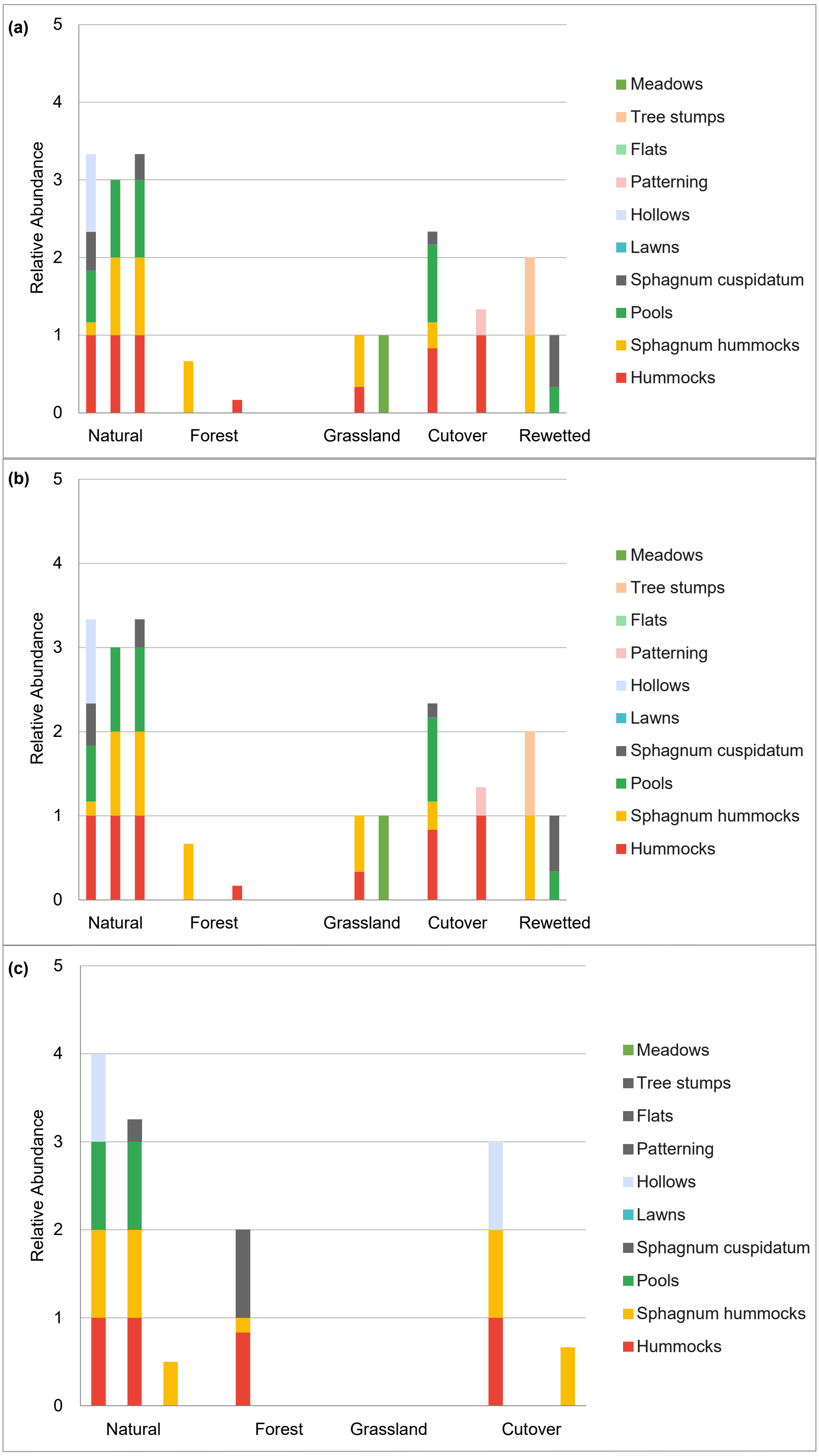


Figure 3.15. Relative microhabitat abundance in (a) raised bog, (b) lowland blanket bog and (c) mountain blanket bog sampling sites.

3.6 Vegetation Profile of Irish Peatlands with Different Land Use Categories and Management Regimes

A vegetation assessment was carried out at each soil sampling location (270 points) in conjunction with other abiotic parameters (see the end-of-project Technical Report). A vegetation assessment scheme developed in the context of previous peatland research was adopted (Renou-Wilson *et al.*, 2018).

Our results confirm that the use of peatlands and associated allogenic[4] factors have affected the vegetation of natural peatlands across a broad spectrum. This heterogeneity is accentuated by additional "external factors", such as local climate, topography and geology (groundwater drainage), reinforcing the "each peatland site is unique" adage. Except for the extreme case of cutaway peatlands, where the vegetation is completely absent, the spatial patterns of vegetation communities are strong indicators of peatland type and conditions, and are unique to their location and their management. Even grassland or forestry peatlands display a high level of heterogeneity between sites.

The relative abundance of microhabitats (i.e. the number of quadrats containing a microhabitat out of the total number of quadrats examined) was much lower in all LUCs than in natural sites (Figures 3.15–3.17). The high microhabitat diversity of natural bogs is in stark contrast to their conspicuous absence in all other peatland LUCs. This is particularly true for raised bogs, which display the greatest microhabitat diversity, with the Mongan and Scohaboy sites each having five microhabitats. Pools were observed in all but one natural bog type and in three out of the four rewetted sites. Nonetheless, rewetted cutover bogs have shown that they are on a trajectory that could bring back the full microhabitat diversity of natural bogs (Figure 3.16). The results also support previous studies that have demonstrated the importance of cutover bogs in providing biodiversity value (Figure 3.17). This confirms the successful outcomes of rewetting all types of managed drained peatlands.

The role of vegetation composition (or its absence) is central in determining the GHG dynamics of natural and managed peatlands. While certain assemblages (ecotopes) can be used as a proxy for the hydrological regime of a site, and thus for predicting GHG dynamics (Regan *et al.*, 2020), the heterogeneity of vegetation composition within and between sites, together with their associated local hydrological regimes, makes their modelling difficult for GHG predictions. The

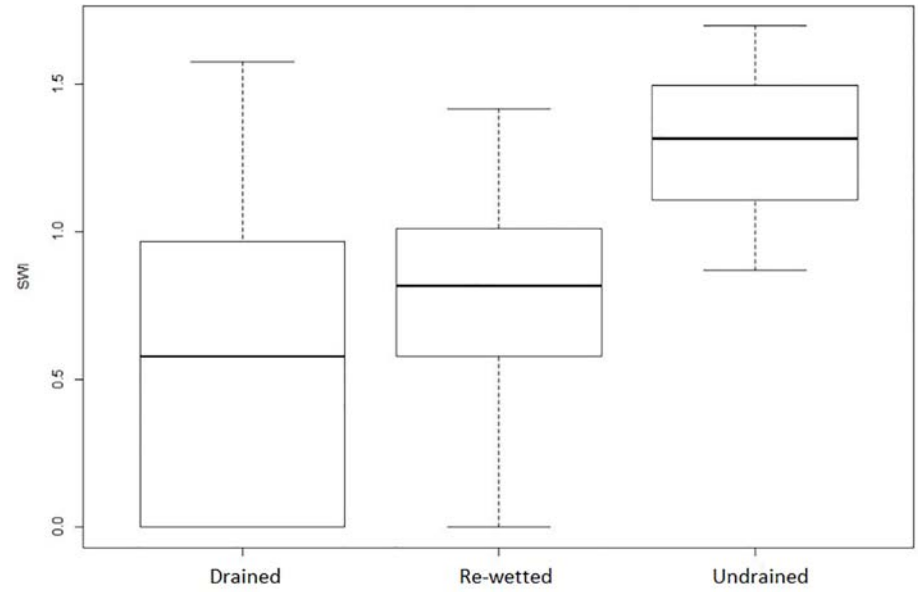


Figure 3.16. Boxplot of Shannon–Weiner index (SWI) values at each sampling point according to the management type at that point (drained, rewetted, undrained).

---

[4] Pertaining to factors from outside the system, e.g. habitats altered by drainage, cutting or fertiliser application.

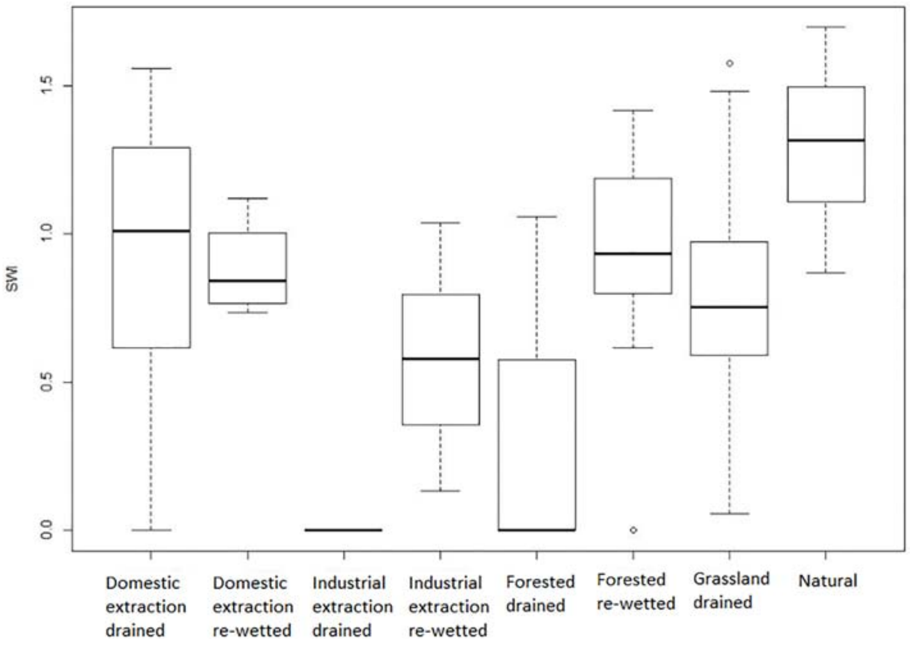


Figure 3.17. Boxplot of Shannon–Weiner index (SWI) values at each sampling point according to the management type at that point.

complexity of monitoring such spatial heterogeneity and attributing relative emission factors seems very high and can only be modelled using innovative methods. Although the development of aerial imagery could help map these mosaic sites, certain barriers are still present, for example overlapping spectral signatures of different vegetation communities or non-recognition of existing drainage systems.

4 Greenhouse Gas Field Measurements at Cutover Peatlands

4.1 Introduction

Natural peatlands have been shown to be long-term carbon sinks (e.g. Koehler *et al.*, 2011), as the amount of CO_2 sequestered by the ecosystem is greater than carbon losses though CH_4 emissions to the atmosphere and DOC movement to water bodies. However, there is a fundamental shift in GHG dynamics when these natural sites are drained, and the peatland invariably switches to acting as a persistent net CO_2 source (IPCC, 2014). Rewetting offers the potential to reduce CO_2 emissions (Wilson *et al.*, 2016a) and, in some cases, return the CO_2 sequestration function characteristic of natural peatlands (Wilson *et al.*, 2016b; Nugent *et al.*, 2018). At the same time, CH_4 emissions are likely to increase following rewetting (Huth *et al.*, 2013; Renou-Wilson *et al.*, 2019). Given that the magnitude of GHG exchange following rewetting is likely to vary considerably between peatland sites (Wilson *et al.*, 2016a), countries are encouraged to develop sufficient data capacity to permit reporting of GHG emissions/removals at the country-specific Tier 2 level (IPCC, 2014). In this study, we measure, model and report multi-year annual GHG emissions/removals at two peatland sites in Ireland.

4.2 Moyarwood, County Galway

4.2.1 Study site

The study site is a raised bog at Moyarwood, County Galway, Ireland (latitude 53.347098, longitude –8.515251, elevation 97 m above sea level), with a 30-year mean (1971–2000) annual temperature of 9.9°C and mean annual precipitation of 1193 mm (data from the Athenry Met Éireann station). The site had undergone peat extraction (domestic) on the margins for decades and was extensively drained (drains located every 15 m) in the 1980s in preparation for milled peat extraction. However, the site was never subsequently developed for peat extraction, and a vegetation cover remained *in situ* between the drains. The drains were active until a rewetting programme commenced in 2012, which involved blocking the drains with peat dams at regular intervals (generally at any point where there was a fall in the drain level of 10 cm). The average peat depth within the site is 4.40 m and the peat is composed mainly of humified *Sphagnum* peat overlying limestone parent material. A detailed site description and the associated field measurements/modelling can be found in the end-of-project Technical Report. GHG flux measurements using chamber methods commenced in April 2013 and ended in March 2018.

4.2.2 Results

Environmental variables

Soil temperature showed strong seasonal variability in both the drained and rewetted areas (Figure 4.1). The lowest and highest values were always observed in the drained area in winter and summer, respectively, and daily variability was always more pronounced in the drained area. However, mean annual temperature was consistently greater in the rewetted area (Figure 4.1).

In the drained area, the observed WTL remained 38–67 cm below the peat surface for the duration of the study (Figure 4.2); moreover, seasonal variability was not evident. In contrast, the WTL in the rewetted area remained above the peat surface for most of the study period, with the exception of short periods in the summers of 2013, 2014 and 2017.

Net ecosystem exchange

The drained site was a net CO_2 source in all five years (Figure 4.3a, Table 4.1). Emissions were lowest in year 3 (~112 g C m^{-2} y^{-1}) and greatest in year 2 (~164 g C m^{-2} y^{-1}). In years 1, 3 and 4, the drained site functioned as a net CO_2 sink until early summer, but then switched to acting as a CO_2 net source as soil temperatures increased. In years 2 and 5, the drained site was a net CO_2 source for the whole year. In contrast, the rewetted site was a net CO_2 sink in all five years (Figure 4.3b, Table 4.1). Uptake

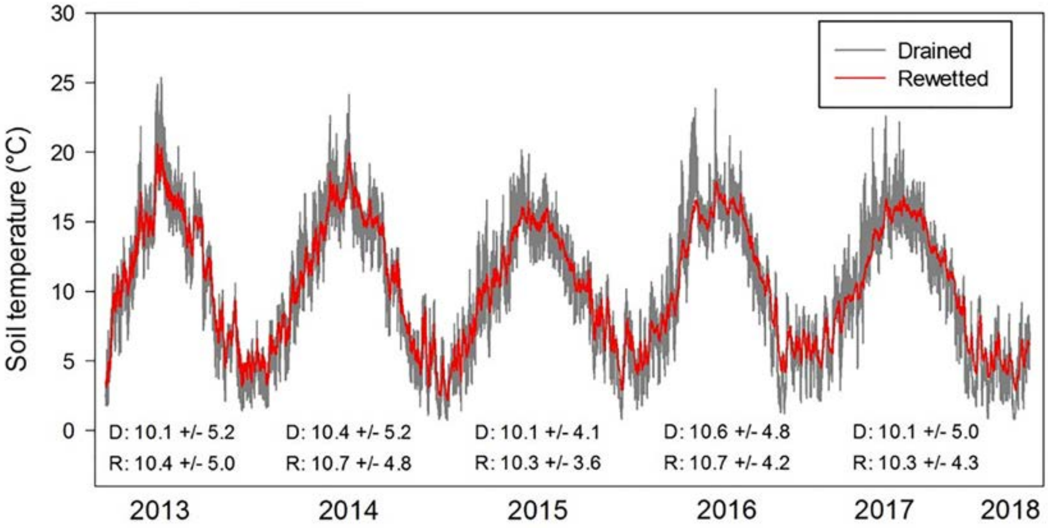


Figure 4.1. Hourly soil temperature (°C) at 5 cm depth in the drained (grey) and rewetted (red) areas at Moyarwood, County Galway. Mean annual soil temperatures for drained (D) and rewetted (R) areas and standard deviations are shown.

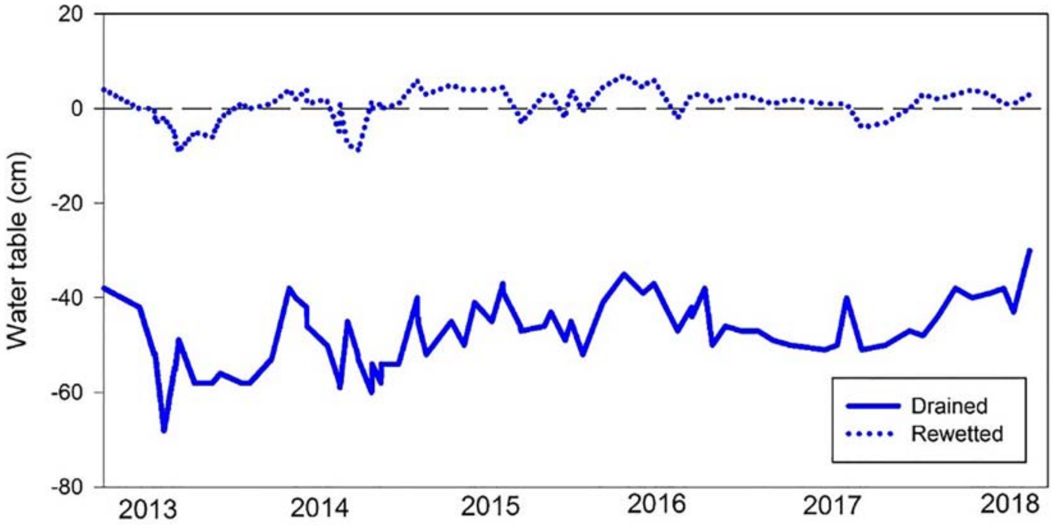


Figure 4.2. Water table level (cm) in the drained (solid blue line) and rewetted (dotted blue line) areas of the study site at Moyarwood, County Galway. The water table was manually measured during field visits and water table values were linearly interpolated between site visits.

was lowest in year 1 (–19.5 g C m^{-2} y^{-1}), with small net losses of CO_2 evident from July to December of that year. Throughout years 2–5, the rewetted site was a constant sink for CO_2, with net annual uptake ranging from around –77 to –148 g C m^{-2} (Figure 4.3b, Table 4.1).

Methane and nitrous oxide fluxes

Fluxes at the drained site were very low and ranged from a small uptake to small emissions (Figure 4.4a). However, a statistically significant relationship between fluxes and environmental variables was not established during the modelling process. Instead, annual emissions were estimated by linearly interpolating fluxes between measurement dates to provide values of 0.1–0.8 g C m^{-2} y^{-1} (Table 4.1). Methane emissions at the rewetted site exhibited strong seasonal variations, driven mainly by soil temperatures. Typically, the lowest emissions were observed during the winter months (December to February), and the greatest emissions were seen

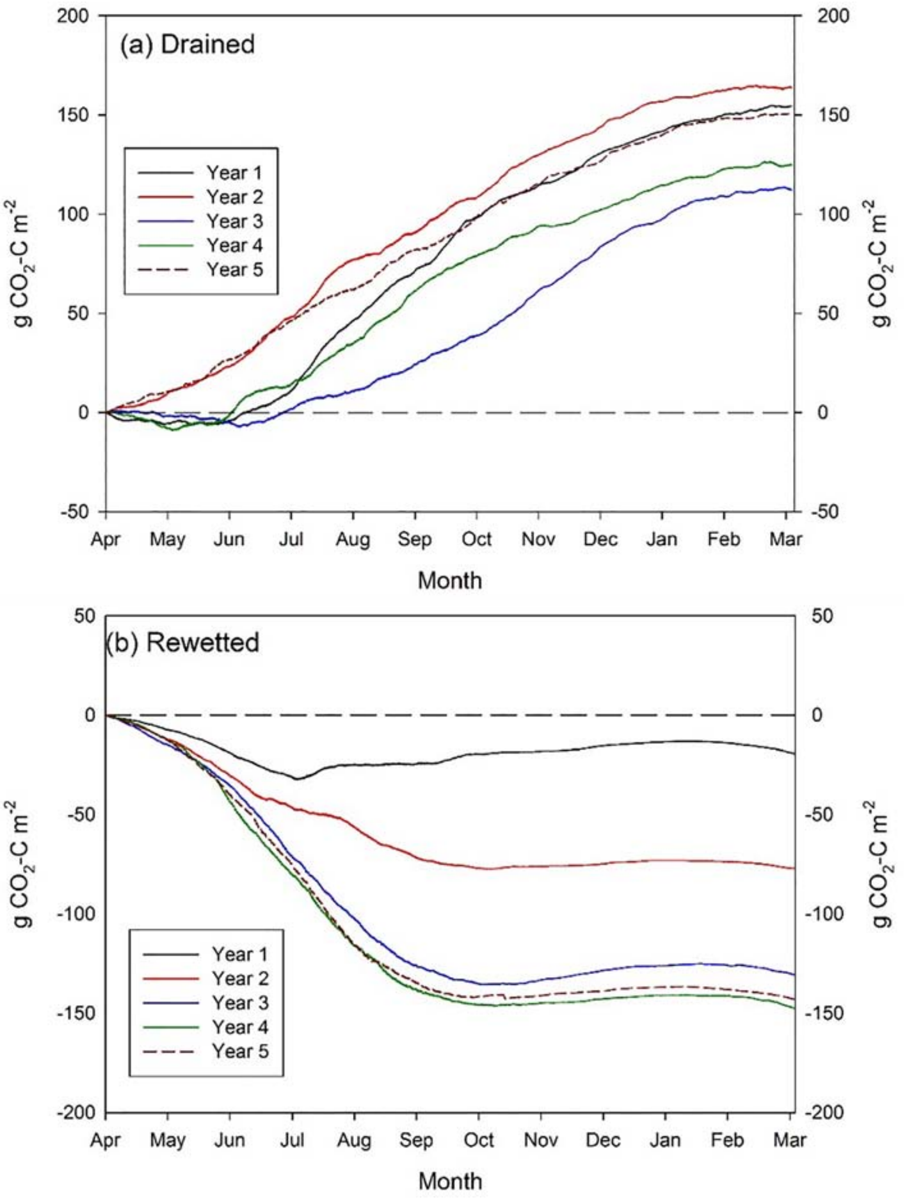


Figure 4.3. Cumulative net ecosystem exchange (g CO_2-C m^{-2}) in the (a) drained and (b) rewetted areas in Moyarwood from April 2013 to March 2018 (years 1–5). Positive values indicate a net loss of CO_2 to the atmosphere and negative values indicate net uptake of CO_2 by the peatland.

in summer (June to August). Annual CH_4 emissions were very similar between years, ranging from 18.6 g C m^{-2} y^{-1} to 20.6 g C m^{-2} y^{-1}. Nitrous oxide (N_2O) fluxes were not detectable at either the drained or rewetted sites during the study.

Net ecosystem carbon balance

To provide a net ecosystem carbon balance (NECB) for both sites, data from Regan *et al*. (2020) were used to provide values for the expected losses of DOC from both sites. Considerable interannual variation in NECB was observed for both sites. The drained site had a positive NECB (i.e. it was a carbon source) throughout the study period, with a 5-year average of 157 g C m^{-2} y^{-1} (which equates to 1.57 t C ha^{-1} y^{-1}). The NECB in the drained site was dominated by the CO_2 component, which accounted for around 90% of the total (Table 4.1).

The NECB in the rewetted site ranged from 5.7 g C m^{-2} y^{-1} in year 1 (i.e. it was a carbon source) to –121.9 g C m^{-2} y^{-1} in year 4 (i.e. it was a carbon sink). Again, CO_2 was the dominant component of the NECB, but the contribution of CH_4 was more pronounced than in the drained site (Table 4.1).

Table 4.1. Net ecosystem carbon balance for the drained and rewetted areas in Moyarwood from April 2013 to March 2018 (years 1–5). Positive values indicate a net loss of carbon to the atmosphere and negative values indicate net uptake of carbon by the peatland

Year	CO_2 (g C m^{-2} y^{-1})	CH_4 (g C m^{-2} y^{-1})	DOC^a (g C m^{-2} y^{-1})	NECB (g C m^{-2} y^{-1})
Drained				
1	154.2	0.6	15.4	170.2
2	163.8	0.8	15.4	180.0
3	111.9	0.1	15.4	127.4
4	124.9	0.1	15.4	140.4
5	150.8	0.7	15.4	166.9
5-year average	141.1	0.5	15.4	157.0
Rewetted				
1	–19.5	18.76	6.4	5.7
2	–77.3	20.58	6.4	–50.3
3	–131.1	19.01	6.4	–105.7
4	–147.8	19.53	6.4	–121.9
5	–143.0	18.62	6.4	–118.0
5-year average	–103.7	19.3	6.4	–78.0

^{a}DOC values taken from Regan *et al*. (2020).

4.3 Clara, County Offaly

4.3.1 Study site

Clara bog is a Special Area of Conservation (SAC) located in County Offaly (latitude 53.3205, longitude –7.62774, elevation 57 m above sea level), with a 30-year mean (1971–2000) annual temperature of 9.6°C and mean annual precipitation of 820.4 mm (data from the Birr Met Éireann station). The site has over 400 ha of uncut peatland (Regan *et al*., 2020) and is demarcated as Clara East and West, split by a road that runs approximately north to south though the middle of the bog. This study focused on Clara West, which has a greater area of active raised bog but has been historically affected by a network of marginal drains associated with peat extraction located on the southern boundary of the site. These drains were largely blocked in 1996, and further restoration works implemented in 2016 have increased the area of active raised bog present (Regan *et al*., 2020). The vegetation on Clara bog has been classified in previous work using the ecotope descriptions devised by Schouten (2002).

4.3.2 Net ecosystem exchange

The net ecosystem exchange (NEE) of CO_2 was measured using eddy covariance techniques. This method is explained in detail in Moncrieff *et al*. (1997); however, the system at Clara bog is equipped with an infra-red gas analyser (LI-7200 LICOR Biosciences, Lincoln, NE, USA), a 3-D sonic anemometer (Gill Windmaster, Gill Instruments, Lymington, UK) and an associated meteorological station. The *in situ* meteorological measurements were further complemented by data from the Met Éireann station at Horseleap, County Offaly, which is approximately 7 km north of the site. The eddy covariance tower was deployed in February 2018 and was operational during the exceptional climatic conditions observed across Europe in 2018 (Peters *et al*., 2020). At the Clara site, mean daily air temperatures followed a characteristic seasonal pattern in both 2018 and 2019, when the peak average temperatures (~20°C) were associated with summer periods and the middle of the growing season (Figure 4.5).

The total daily incident irradiance in the photosynthetically active radiation (PAR) wavelengths also followed a similar seasonal pattern (Figure 4.6), with peak rates (~35 mmol PAR m^{-2} d^{-1}) occurring during the growing season. Precipitation received at the site (Figure 4.7a–c) demonstrated variability between years; 2018 (733.3 mm) was a drier year than both 2019 (1034.5 mm) and the 30-year mean (820.4 mm). Monthly patterns of precipitation varied between years and in comparison with the 30-year

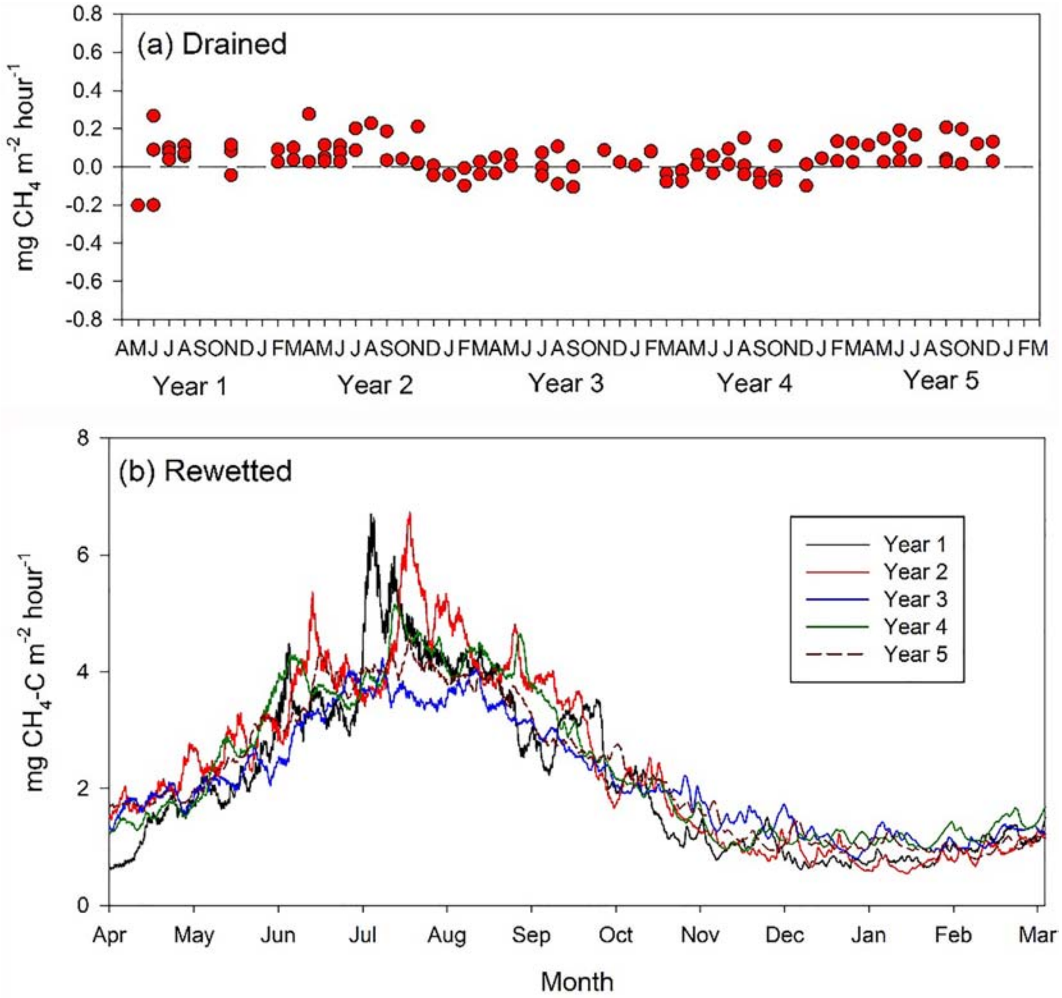


Figure 4.4. (a) Measured methane (CH_4) fluxes (mg C m^{-2} hour^{-1}) in the drained area and (b) modelled CH_4 fluxes (mg C m^{-2} hour^{-1}) in Moyarwood from 2013 to 2018 (years 1–5). Positive values indicate a net loss of CH_4 to the atmosphere and negative values indicate net uptake of CH_4 by the peatland.

mean; in 2018, precipitation received between February and October was lower than in the same period of 2019 and lower than the 30-year mean (Figure 4.7a), and the total amount of precipitation received during the growing season (Figure 4.7c) in 2018 (463.8 mm) was lower than both the value in 2019 (858.0 mm) and the 30-year mean (599.6 mm). In this study, the start of the growing season was defined as the first day of the year when the mean diurnal temperature had exceeded 5°C for five consecutive days, and the end of the growing season was determined as the first day when the mean diurnal temperature had fallen below 5°C for five consecutive days. The period between constitutes the length of the growing season (LGS).

The variability in the hydrological regime of the site was also observed through measurements of WTL at the central ecotope, which varied throughout the year in both 2018 and 2019 (Figure 4.8). A greater reduction in the mean daily WTL at the central ecotope was observed in 2018 than in 2019, with maximum reductions in WTL of approximately –15 cm in 2018 compared with approximately –10 cm in 2019. In addition, an extended period when the water table was below the surface of the site was observed in 2018. Dry periods in peatland systems have been arbitrarily defined as periods of 1 week or longer when the WTL is at or lower than 5 cm below the surface of the peat (Helfter *et al*., 2015). In this study, in 2018 an extended dry period was observed, with over 150 consecutive days when the water table was below 5 cm (Figure 4.8).

The patterns of carbon uptake through photosynthesis (gross primary production, GPP) and release through

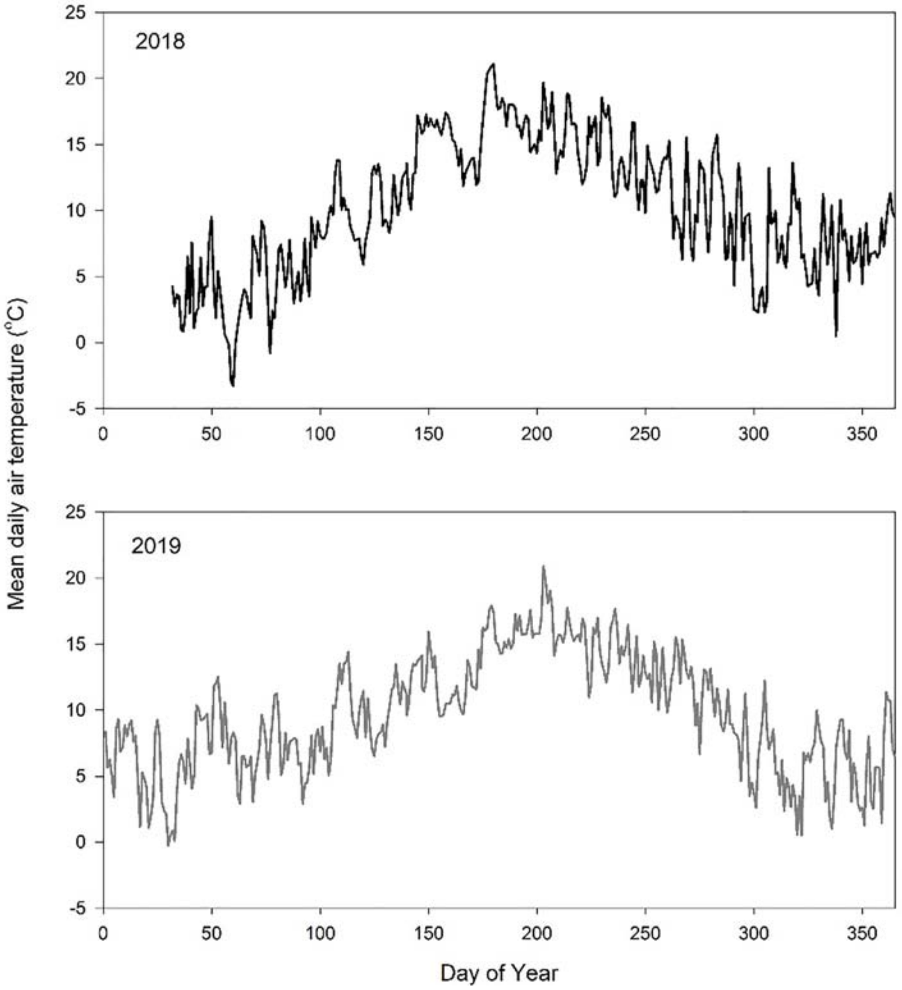


Figure 4.5. Mean daily air temperature (°C) at the Clara bog site in 2018 (upper panel) and 2019 (lower panel).

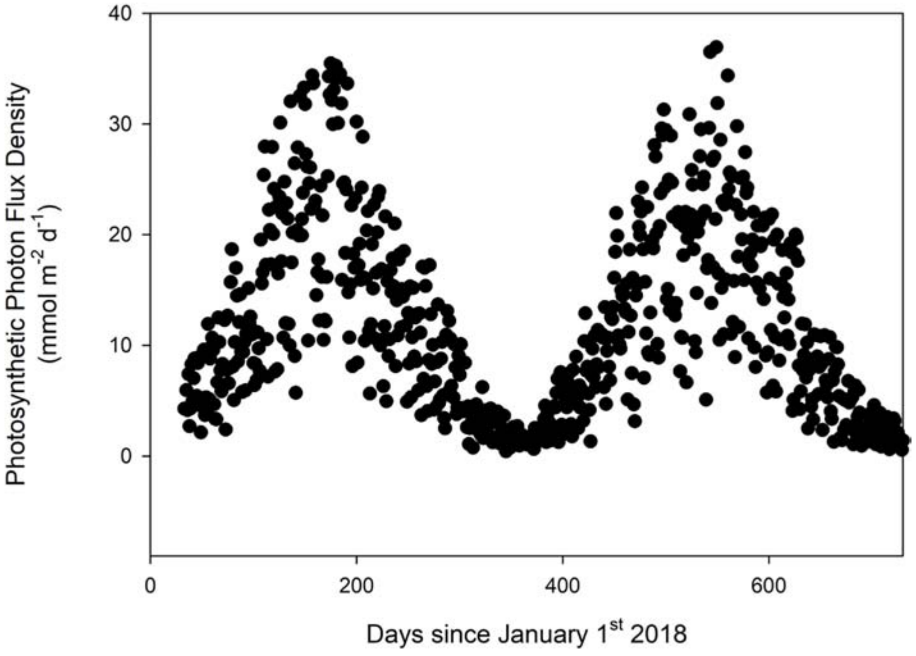


Figure 4.6. Daily incident photosynthetic photon flux density at the Clara bog site in 2018 and 2019.

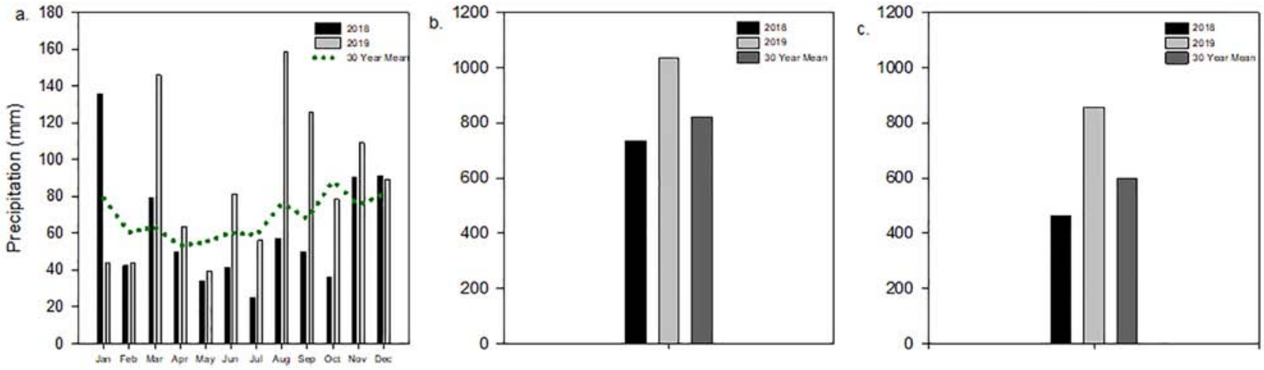


Figure 4.7. Monthly (a), annual (b) and growing season (c) precipitation (mm) at the Clara bog site (data for 2018 and 2019 were derived from the Met Éireann station at Horseleap, County Offaly). The 30-year mean data were derived from data from the Met Eireann station at Birr, County Offaly.

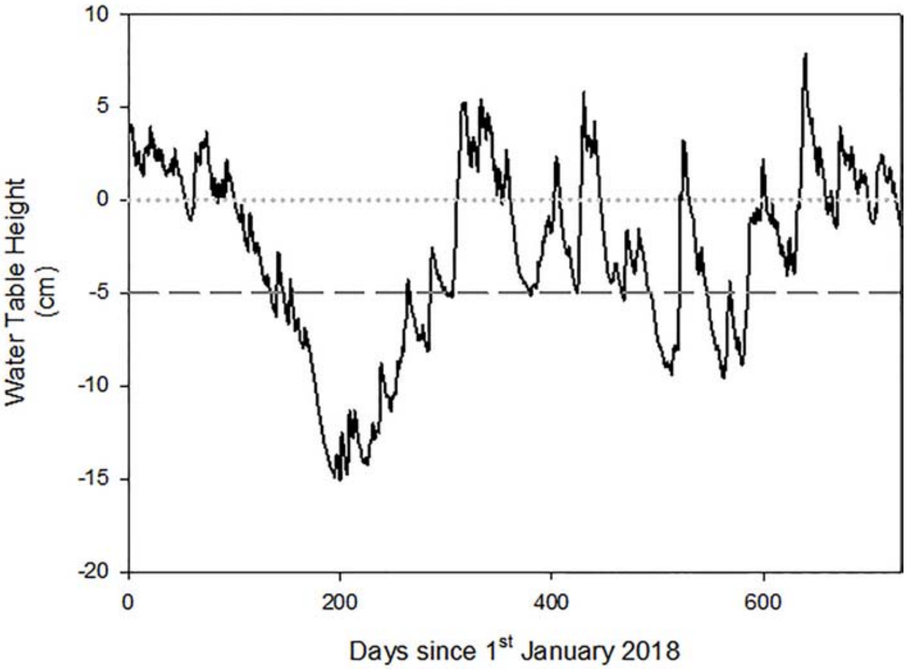


Figure 4.8. Mean daily water table (cm) for the central ecotope in Clara bog for 2018 and 2019. The horizontal dotted grey line indicates the peat surface, and the horizontal dashed grey line indicates the point at which the mean daily water table drops below 5 cm from the peat surface.

ecosystem respiration (R_{eco}) responded to changes in WTL in both years, but the relationship was stronger in 2018 than 2019 (Figure 4.9). The data suggest a stronger coupling of both components of NEE to WTL during the drier year (2018).

The net sum of the carbon budget components is shown in Table 4.2, which shows that the area studied acted as a net source of 53.5 g C m^{-2} y^{-1} in 2018 but was a net sink of –125.2 g C m^{-2} y^{-1} in 2019. The difference between the two years was driven by lower rates of carbon assimilation (–71 g C m^{-2} y^{-1}) and greater rates of carbon release (107.5 g C m^{-2} y^{-1}) in 2018 than in 2019. Also of note are the differences in the length of the growing season between years (231 days in 2018 compared with 272 days in 2019), and the differences in growing season NEE (NEE$_{GS}$ –0.03 C m^{-2} d^{-1} in 2018 compared with –0.58 g C m^{-2} d^{-1} in 2019). The NEE$_{GS}$ data provide a further example of the dominance of respiratory losses during the growing season in 2018, which acted as the key driver of the net ecosystem carbon dynamics in this particular year.

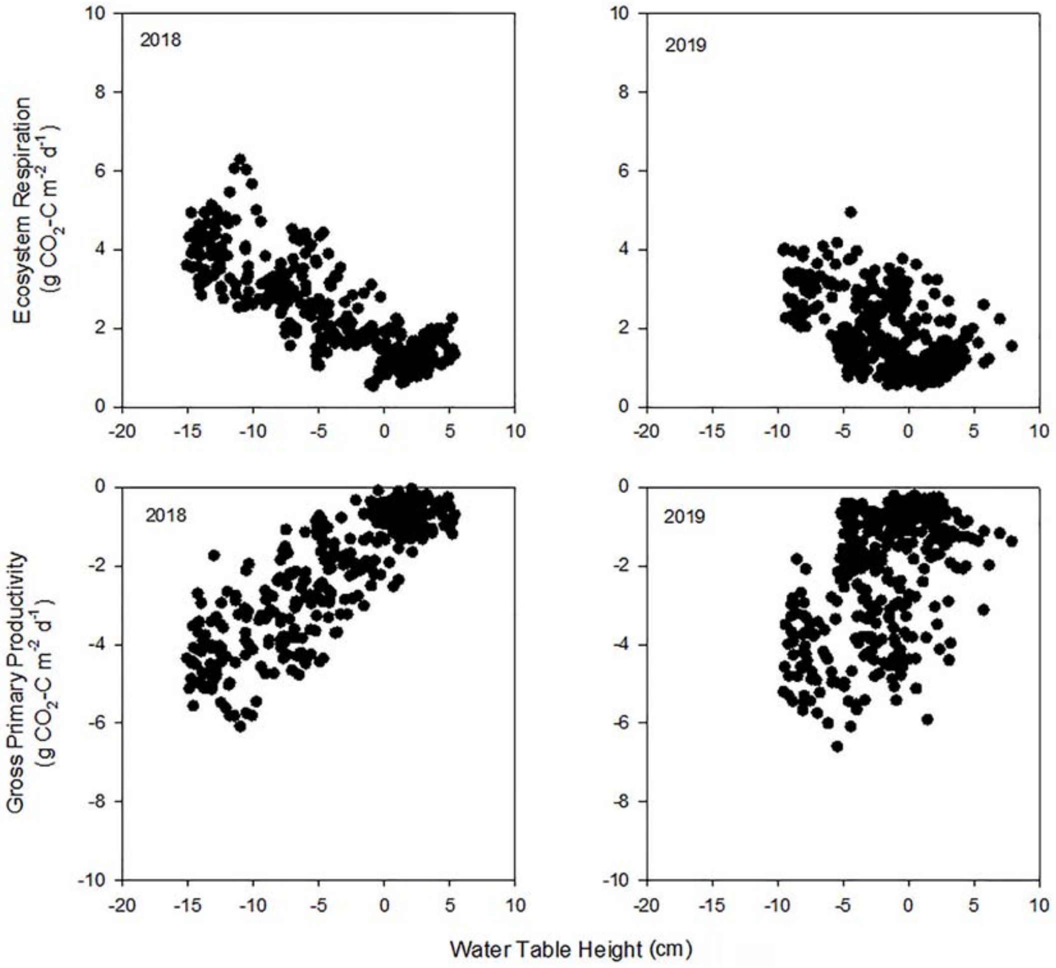


Figure 4.9. The relationship between mean daily water table level (WTL) at the central ecotope and the components of net ecosystem carbon exchange in Clara bog in 2018 and 2019. The upper panels show the relationship between WTL and ecosystem respiration in both years, while the lower panels show the relationship between WTL and gross primary production in both years.

Table 4.2. Annual values for gross primary productivity, ecosystem respiration and net ecosystem exchange for the Clara bog study site in 2018 and 2019. Also shown are the length of the growing season (LGS) and the net ecosystem carbon dynamics during the growing season (NEE_{GS}) and the dormant season (NEE_{DS}) in each year

	GPP	R_{eco}	NEE		NEE_{GS}/LGS	NEE_{DS}/LGS
Year	($g\,C\,m^{-2}\,y^{-1}$)			Growing season (days)	($g\,C\,m^{-2}\,d^{-1}$)	
2018	–753.1	806.6	53.5	231	–0.03	0.45
2019	–824.3	699.1	–125.2	272	–0.58	0.37
2-year average	–788.7	752.85	–35.9	252	–0.31	0.41

4.4 Discussion

The results from this study provide valuable information for the management of Irish peatlands, particularly regarding their potential to mitigate the effects of climate change. Under a “business-as-usual” approach, where a peatland has been drained, we can expect that CO_2 emissions will persist indefinitely in the absence of mitigation measures. The drained site at Moyarwood released an average of 1.41 t C ha^{-1} y^{-1} (or 5.2 t CO_2 ha^{-1} y^{-1}) to the atmosphere. While this value is lower than the IPCC Tier 1 emission factor for peatland sites drained for extraction (2.8 $\mathrm{t\,C\,ha^{-1}\,y^{-1}}$) (IPCC, 2014), it remains problematic (from a GHG reporting point of view) when, or indeed if, this LUC is scaled up to the national level. Wilson *et al*. (2013a) estimated that domestic peat extraction in Ireland results in emissions of 673,315 t of carbon per year. Our results here, which agree with the meta-analyses performed by Wilson *et al*. (2015) for peat extraction sites in Ireland and Britain, would indicate that national emissions in this LUC could be closer to 860,000 t of carbon per year (or 3.15 $\mathrm{Mt\,CO_2\,y^{-1}}$), based on the areas provided by Malone and O'Connell (2009). Interestingly, domestic (residential) peat extraction is estimated to account for only 400 ha in the most recent national inventory report (Duffy *et al*., 2020), which would suggest that national GHG emissions from this LUC are strongly underestimated. Moreover, CH_4 emissions from drained vegetated peatland sites do occur (Figure 4.4a and Table 4.1), which is highly relevant given the global warming potential and radiative forcing effect of this gas (Günther *et al*., 2020). Our annual values of 0.5 $\mathrm{g\,C\,m^{-2}\,y^{-1}}$ (equivalent to 5 $\mathrm{kg\,C\,ha^{-1}\,y^{-1}}$) are close to the Tier 1 emission factor derived for drained nutrient-poor peatlands (6.1 $\mathrm{kg\,C\,ha^{-1}\,y^{-1}}$) in the temperate zone (IPCC, 2014), and for German peat extraction sites (4.2 $\mathrm{kg\,C\,ha^{-1}\,y^{-1}}$) (Tiemeyer *et al*., 2020).

This study confirms the potential of some rewetted peatland sites to act as net carbon sinks, and over a very short timeframe following drain blocking. Water levels at the rewetted site in Moyarwood were consistently 40–50 cm higher than in the drained area throughout the 5-year study period (Figure 4.2), and contributed substantially to the observed changes in carbon dynamics, vegetation composition and soil temperatures at the site. For the latter, the higher WTL led to reduced fluctuations in the daily soil temperatures (Figure 4.1), thereby acting as a "buffer" to external changes. Moreover, water levels at the rewetted area in Moyarwood were comparable to those of the active raised bog area in Clara bog (Figure 4.8), which would suggest that the drain blocking at the rewetted site has been very successful in raising and maintaining the water level. Unfortunately, the Moyarwood study finished at the end of March 2018, and so we were not able to quantify GHG fluxes during the drought period in the spring/summer of that year.

Annual NEE at Clara bog exhibited very strong interannual variation (Table 4.2), with a small loss observed in 2018 followed by strong uptake in 2019. This variation was driven primarily by the drier conditions in 2018, by the much wetter conditions in 2019 (Figure 4.7) and potentially by the much longer growing season in the second year of the study (Table 4.2). Dry periods and limited water availability in peatlands have been observed to have a greater impact on carbon losses through respiration than the carbon uptake/assimilation capacity of these ecosystems (Helfter *et al*., 2015). In this study, similar trends were observed when the extended dry period in 2018 resulted in ecosystem respiration dominating the carbon flux dynamics over the growing season at Clara bog (Figure 4.9, Table 4.2).

Long-term GHG monitoring of peatland sites can provide robust baseline datasets, which can allow the effects of external and internal stressors to be appropriately evaluated (Wilson *et al*., 2016b), and interannual variation to be suitably appraised. While there are approximately 10 long-term GHG datasets from natural peatlands in the northern hemisphere (see Figure 7 in Wilson *et al*., 2016b), datasets of more than 3 years for rewetted peatland sites remain scarce. In a 5-year study at a rewetted industrial cutaway at Bellacorick, County Mayo, Wilson *et al*. (2016b) reported that the site was a CO_2 sink of 104 $\mathrm{g\,C\,m^{-2}\,y^{-1}}$ and a CH_4 source of 9 $\mathrm{g\,C\,m^{-2}\,y^{-1}}$. In Canada, Nugent *et al*. (2018) reported that a restored peatland was a net CO_2 sink of 90 $\mathrm{g\,C\,m^{-2}\,y^{-1}}$, a CH_4 source of 4.4 ± 0.2 $\mathrm{C\,m^{-2}\,y^{-1}}$ and a DOC source of 6.9 $\mathrm{g\,C\,m^{-2}\,y^{-1}}$, resulting in a NECB of 78 $\mathrm{g\,C\,m^{-2}\,y^{-1}}$. These values are close to those reported here for Moyarwood (Table 4.1).

Following rewetting, CH_4 emissions increase substantially (IPCC, 2014), as strongly anaerobic conditions are recreated in the formerly drained soils. Annual CH_4 emissions from our two sites varied considerably. Our study at Moyarwood commenced in tandem with the blocking of the drains (in early 2013). Given that a vegetation layer was present at the surface, it is probable that the rise in water level resulted in inundation of some of the vegetation communities, thereby providing a labile carbon source for methanogenic bacteria (Urbanová and Bárta, 2020). The high annual CH_4 emissions observed at Moyarwood (equivalent to 193 kg C ha^{-1} y^{-1}) are over twice the magnitude of CH_4 emission factors derived for nutrient-poor peatlands in the temperate zone (92 kg C ha^{-1} y^{-1}) (IPCC, 2014), and for CH_4 emissions at Clara bog reported by previous studies (Regan *et al*., 2020). Nevertheless, the newly rewetted site at Moyarwood functioned as a net carbon sink for 4 out of the 5 years of the study (Table 4.1).

5 Biogeochemical Process-based Modelling to Predict Greenhouse Gas Fluxes from Irish Peatlands Affected by Anthropogenic Changes

5.1 Introduction

Biogeochemical process-based models are known to have significant potential to quantify the effects of management practices on GHG emissions in different ecosystems (Olander *et al*., 2011). In this chapter, the main focus is on biogeochemical modelling of GHG fluxes in Irish peatlands using the ECOSSE model (Smith *et al*., 2010). The particular focus of this study was on the development of approaches to improve ECOSSE process-based biogeochemical modelling to potentially contribute towards the future development of Tier 3 methodologies for estimating peatland GHG emissions in Ireland. These modelling improvements should allow the inclusion of different peatland LUC/management categories, such as drainage and rewetting/restoration.

The overall goal of this study was to perform modelling and the prediction of GHG fluxes associated with different land use and peatland management categories, with the primary focus on draining and rewetting. This included the development of modelling approaches that would enable the application of the ECOSSE model to investigate the impacts of drainage and rewetting in peatlands on GHG fluxes, and enabling the application of ECOSSE to investigate the main underlying factors (natural/environmental, anthropogenic) influencing GHG emissions in peatlands, to contribute to a better understanding of peatland functioning.

5.2 Study Background

The need for potential model upgrading was identified during the initial stages of this study, especially with respect to ECOSSE model limitations in inputs regarding the LUC/management of peatlands and the water table. Potential LUCs were identified for the future modelling needs of peatland sites in Ireland, for example "natural", "bare-peat" or "drained", "rewetted". This required the introduction of new peatland parameters for vegetation into the ECOSSE model, as well as the version of the model that contained the water table module. For this study, the James Hutton Institute, Aberdeen, and the Environmental Modelling Group, University of Aberdeen, provided the required vegetation parameters for peatlands for ECOSSE, as well as the version of the model (ECOSSE-v.6.2b-wt) with the water table module included. Test simulations were run (using the Blackwater peatland as an example) during which the options for running the obtained model version and peatland parameters for vegetation were explored. This enabled the identification of potential model limitations and the need for further developments and upgrading, especially for the purpose of applying the ECOSSE model for simulating GHG emissions in Irish peatlands under drained and rewetted conditions.

The ECOSSE model uses a very simple concept for simulating vertical water movement through the soil profile based on the piston flow approach (Smith *et al*., 2010), and it does not account for the drainage network system that is normally present in drained peatlands, other than via measured water table inputs. The water movement is simulated through a soil profile consisting of a number of user-defined homogeneous soil layers such that the precipitation is added to the top layer and rainwater is distributed downwards by a simple piston flow (Smith *et al*., 2010). Therefore, an improvement of the water table simulation approach was needed, and a new drainage factor was developed to be applied to ECOSSE rainfall input parameters, with the aim of achieving better simulation of GHG fluxes from peatlands under drained and rewetted conditions (Premrov *et al*., 2021).

Modelling in this study used data from two Irish drained (former raised) bogs, Blackwater and Moyarwood, both of which developed drained and rewetted areas on cessation of drainage/drain blocking (Wilson *et al*., 2015; Renou-Wilson *et al*., 2019). The main objective was to develop a new drainage factor (Dfa) parameter, specifically for ECOSSE, which could be easily applied to the model rainfall inputs and would potentially enable manipulation and changes in the simulated water levels (WLs),[5] for example from drained to rewetted conditions. The aim was to achieve improvements in both predicted WLs and predicted CO_2 fluxes (Premrov *et al*., 2021). The modelling approach was based on developing Dfa using empirical data from the Blackwater site and validating its application using data from the Moyarwood site. We also tested the modelling of the WL change from drained to rewetted conditions by evaluating the model's performance against measured water table and CO_2 fluxes at the Moyarwood site (Premrov *et al*., 2021).

5.3 Materials and Methods

5.3.1 Study sites

The Blackwater (BWdr) industrial cutaway peatland was drained in the 1950s for peat extraction, and on cessation of the drainage (in 1999) the landscape remained either drained with bare peat or was naturally rewetted and vegetated. The Moyarwood cutover site (drained in 1983 and rewetted in 2012) remained vegetated because it was not industrially exploited, and it comprises both drained (MOdr) and rewetted (MOrw) vegetated areas. A detailed description of these sites, field measurements, GHG fluxes and water table monitoring is provided in Renou-Wilson *et al*. (2019).

The use of the BWdr, MOdr and MOrw sites for developing the Dfa was as follows:

- Data from the bare peat BWdr site were used for the development and testing of Dfa.
- Data from the MOdr site were used for the validation of the application of the previously developed Dfa in the ECOSSE model.
- Data from the MOrw site were used for further testing of application of Dfa,[6] for drained to rewetted conditions.

The empirical data used were obtained from monitoring of GHG fluxes[7] and water table measurements from 2011 to 2015 for the Blackwater sites and from 2013 to 2017 for the Moyarwood sites, and are explained in detail in Renou-Wilson *et al*. (2019). Because the ECOSSE model can predict CO_2 only as heterotrophic respiration (Rh) (Khalil *et al*., 2013; Flattery *et al*., 2018), the direct comparison of measured versus modelled CO_2 fluxes could be carried out only for BWdr (bare peat, where $R_{eco} = \mathrm{Rh}$); whereas for the vegetated Moyarwood site, Rh had to be estimated from R_{eco} (i.e. measured CO_2), following the method of Hardie *et al*. (2009).

5.3.2 ECOSSE model and main model input parameters

The ECOSSE model is described in detail in Smith *et al*. (2010). In brief, ECOSSE has been derived from concepts of the RothC (Coleman and Jenkinson, 1996) and SUNDIAL (Smith *et al*., 1996) models, and it is a process-based biogeochemical model that can be used for simulations on both organic and mineral soils (Smith *et al*., 2010). The ECOSSE model uses a pool-type approach, with five specific soil organic matter pools: inert organic matter, humus, biomass, resistant plant material and decomposable plant material (Eglin *et al*., 2010). The equations are driven using readily available input variables (Eglin *et al*., 2010). The model assumes that the system is in equilibrium or steady state during the model spin-up for initialisation before it is run forwards (Smith *et al*., 2010). This study used ECOSSE-v.6.2b-wtd model ("site-specific" mode, daily time inputs/outputs), which includes a water table module (Smith *et al*., 2010), and introduced peatland vegetation parameters (i.e. "natural vegetation" and "bare peat") as explained in Premrov *et al*. (2021).

---

[5] The term WL is used to differentiate between simulated WL and measured WTL for the reasons outlined in Premrov *et al*. (2021).

[6] Dfa was applied only for the duration of drained conditions.

[7] The measured CO_2 flux (converted into $g\,CO_2\,m^{-2}\,d^{-1}$ and averaged across replicates) was used in testing and validation of the ECOSSE simulated CO_2 model outputs (in $kg\,CO_2\,ha^{-1}\,d^{-1}$, which were also converted into $g\,CO_2\,m^{-2}\,d^{-1}$).

Information on some of the main ECOSSE model input parameters for Blackwater and Moyarwood are outlined below.

- Daily weather input data:
  - Daily weather inputs[8] [precipitation (mm d^{-1}), mean temperature (daily; °C) and potential evapotranspiration (mm d^{-1})] were obtained from the Weather Research and Forecasting (WRF) Model daily climate datasets for Ireland, available from the Irish Centre for High-End Computing (ICHEC)-ERDDAP, v.1.82 (ERDDAP-ICHEC, 2019)[9] and were processed in R v.3.6.0 (R Core Team, 2019).
- Long-term average weather input data:
  - Long-term average weather data (required during model spin-up) expressed as monthly data for each site were obtained from 30-year Met Éireann long-term average data (Met Éireann, 2012). The potential evapotranspiration was estimated using the method described in Thornthwaite (1948).
- Atmospheric nitrogen deposition:
  - Average atmospheric nitrogen deposition data (kg N ha^{-1}) were estimated for each site from European Monitoring and Evaluation Programme datasets (EMEP, 2018, 2019), which were processed using Python 2.7 (PSF, 2017) and ArcGIS (ESRI, 2018); details on data processing are provided in Premrov *et al*. (2019).
- Location:
  - Latitude input data were obtained from Renou-Wilson *et al*. (2019).
- Main soil parameters:
  - SOC (kg C ha^{-1}) data were obtained from Renou-Wilson *et al*. (2019).
  - pH and bulk density (g cm^{-3}) data were obtained from Renou-Wilson *et al*. (2019).
  - Peat depth (cm) data were obtained from Renou-Wilson *et al*. (2019).

  There are other soil input parameters required in ECOSSE, such as soil–water parameters and texture, which are not listed above; details of these soil input parameters are provided in Premrov *et al*. (2021).
- Water table inputs:
  - Water table [daily values (cm) below surface] data measured at Blackwater (2011–2015) and Moyarwood (2013–2015 drained, 2013–2016 rewetted) sites were obtained from Renou-Wilson *et al*. (2019). Data gap-filling and estimation of missing water table measurements, and further technical details are explained in Premrov *et al*. (2021).
- Vegetation parameters:
  - New vegetation parameters (part of “crop_sun.dat” model files) for the “bare-peat” category (used for Blackwater) and “natural peatland vegetation” category (used for Moyarwood) were provided, together with the ECOSSE-v.6.2b-wtd model, by the James Hutton Institute, Aberdeen, and the Environmental Modelling Group, University of Aberdeen.
  - Yield (t ha^{-1}) for vegetated peat was estimated from van Breemen (1995).

5.3.3 Development of the drainage factor (Dfa) and results on seasonally varying Dfa(i)

To account for the drainage associated with the management of a peatland site, a new Dfa drainage factor was developed to be applied to the ECOSSE model rainfall inputs using data from the BWdr bare-peat site, which was carried out via a “failure/success” approach (by running simulation trials) (Premrov *et al*., 2021).

The process of empirical estimation of Dfa involved three main steps, which are explained in detail in Premrov *et al*. (2021) and are described briefly here:

- **Step 1** involved obtaining the main parameters required for computation of a Dfa by defining the “wt-discrepancy event” (Figure 5.1), based on examining ECOSSE-simulated WL outputs against measured water table and rainfall data.

---

[8] Short-term simulations were run using weather data for 2010–2017 for Blackwater and for 2012–2017 for Moyarwood. For long-term simulations (the drainage periods prior to commencement of on-site measurements, i.e. 60 years for Blackwater and 29 years for Moyarwood), the simulations were run by reusing the earlier WRF-ICHEC weather data and measured water table data – further explanation is provided in Premrov *et al*. (2021).

[9] ERDDAP is ICHEC’s data server (https://erddap.ichec.ie/erddap; accessed 15 October 2021).

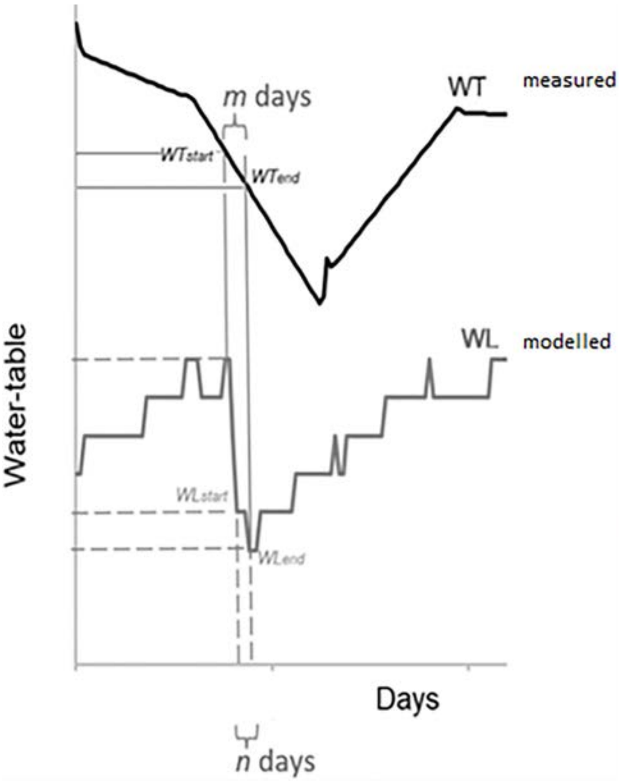


Figure 5.1. Illustrative presentation of the “wt-discrepancy event” that was used to define the main parameters needed in the development and computation of drainage factor. Adapted from Premrov *et al*. (2021); licensed under CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

- **Step 2** involved the development of a series of equations for computation of a Dfa using information from a previously defined “wt-discrepancy event” (Figure 5.1) and parameters obtained during step 1.
- **Step 3** involved further accounting for seasonal variability in the Dfa, i.e. the development of a Dfa that was adjusted for seasonal variability, Dfa(i), which could be applied to the rainfall model inputs (in peatlands under drained conditions) as follows:
  - $\text{Rain}_{adj}(i) = \text{Rain}(i)/\text{Dfa}(i)$ under drained conditions; and
  - $\text{Rain}_{adj}(i) = \text{Rain}(i)$ under rewetted conditions,

  where $\text{Rain}_{adj}(i)$ is the corresponding rainfall value that was adjusted for drainage depending on month (*i*) and is used as an input in ECOSSE, replacing the previous rainfall value, Rain(*i*), obtained from daily climate input data, as illustrated in Figure 5.2. Results for the developed seasonally varying drainage factor Dfa(*i*) for each month (*i*) are provided in Table 5.1.

5.3.4 Process-based modelling of drained and rewetted peatlands using the ECOSSE model with the improved water table simulation approach

Dfa(*i*) was applied to rainfall inputs in the ECOSSE simulation runs at three different sites (BWdr, MOdr and MOrw) to model the WLs and CO_2 fluxes at these sites. Model runs were performed with and without accounting for a long-term drainage period [i.e. either including or excluding 60 years of drainage prior to 2010 at the BWdr site; or 29 years of drainage prior to 2012 at the MOdr site (Premrov *et al*., 2021)]. At MOrw, the simulation was run by introducing a change in water table input from drained[10] to rewetted conditions. Model evaluation involved testing and validation: the testing of the application of Dfa(*i*) to ECOSSE simulations, which was carried out at BWdr, and validation at the MOdr and MOrw sites. Regression analysis of simulated and observed values, and other computed model prediction indices are explained in detail in Premrov *et al*. (2021). Computations were carried out using R (R Core Team, 2019) and accompanying R packages.

5.4 Results

5.4.1 Predicting water levels under drained conditions

ECOSSE simulations of WLs at both BWdr and MOdr sites were significantly improved through the application of Dfa(*i*) to the rainfall input data and by the inclusion of a long-term drainage period at each site. This was evident from plotting the modelled WL and measured water table curves as a time series (Figure 5.3) and from the results from regression analysis of the modelled WL and observed water table [for the coefficient of determination (r^2) and root mean square error (RMSE) values, see Figure 5.3].[11]

---

[10] Including long-term drainage.

[11] Detailed results on modelling WLs from different simulation runs (i.e. inclusion/exclusion of Dfa(*i*) or long-term drainage periods), and results from regression analysis with accompanying model prediction indices, are provided in Premrov *et al*. (2021).

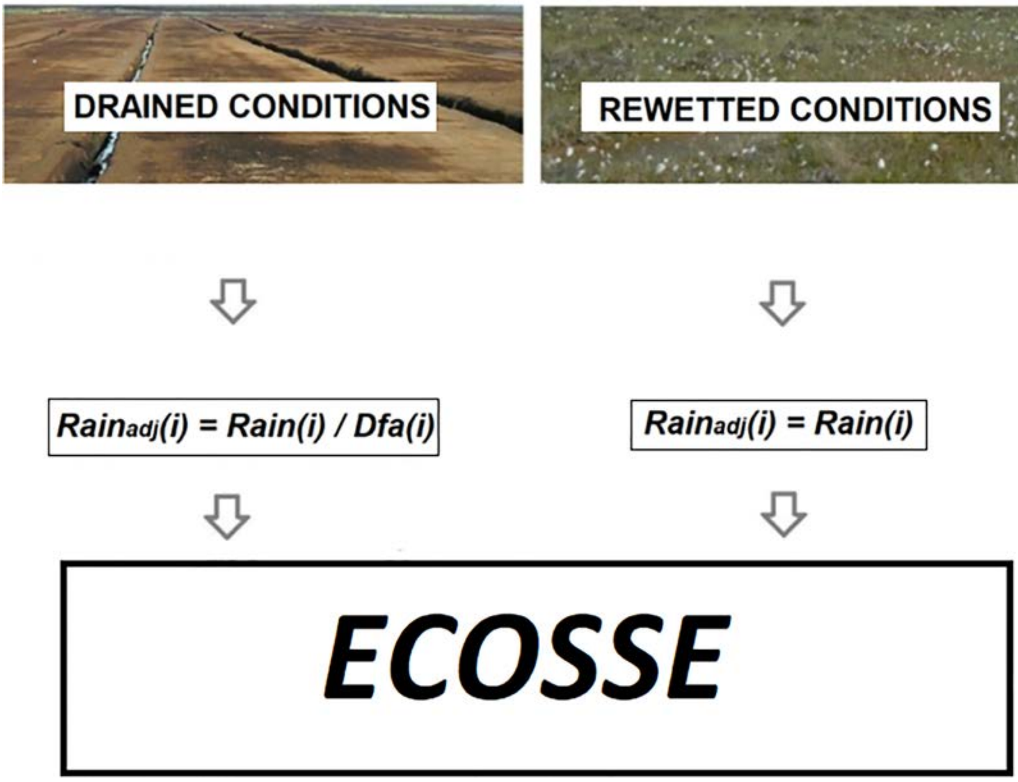


Figure 5.2. Illustrative presentation of application of drainage factor (Dfa) to the ECOSSE rainfall model inputs under drained conditions. Adapted from Premrov *et al.* (2021); licensed under CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

Table 5.1. Results for computed monthly drainage factor [Dfa(*i*)] parameters

Dfa(*i*)	Month (*i*)	Value
DfJan	January	2.86
DfFeb	February	2.86
DfMar	March	2.92
DfApr	April	3.26
DfMay	May	3.32
DfJun	June	2.92
DfJul	July	2.98
DfAug	August	3.11
DfSept	September	2.92
DfOct	October	2.92
DfNov	November	2.95
DfDec	December	2.95

Adapted from Premrov *et al.* (2021); licensed under CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

The results further indicate that running simulations that account for long-term drainage periods at drained peatland sites is recommended for modelling WL, even when there is an absence of measured water table and climate data for previous years (i.e. during these periods without measurements, the long-term simulations were run by reusing the existing measured weather and water table data from later years).

5.4.2 *Predicting CO_2 fluxes under drained conditions*

The ECOSSE simulations of CO_2 fluxes at the BWdr and MOdr sites were significantly improved through the application of Dfa(*i*) to the rainfall input data and by the inclusion of a long-term drainage period at each site. This was evident from the results from regression analysis of the modelled CO_2 fluxes and observed Rh (where $Rh = R_{eco}$ for the BWdr bare peat site; the r^2 and RMSE values are reported in Figure 5.4).[12]

---

[12] Detailed results on modelling CO_2 fluxes from different simulation runs (i.e. inclusion/exclusion of Dfa(*i*) or long-term drainage periods) and the results from the regression analysis with accompanying model prediction indices are provided in Premrov *et al.* (2021).

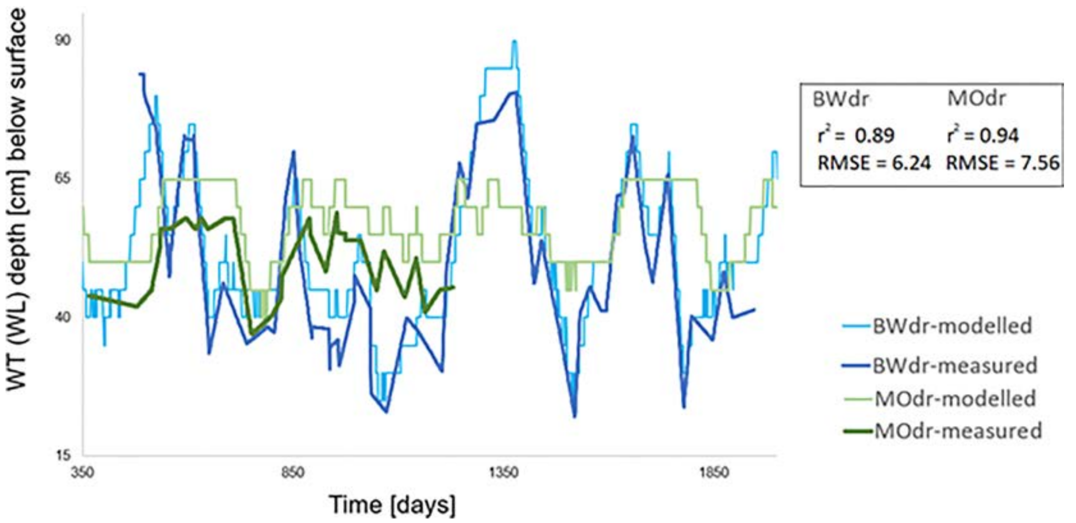
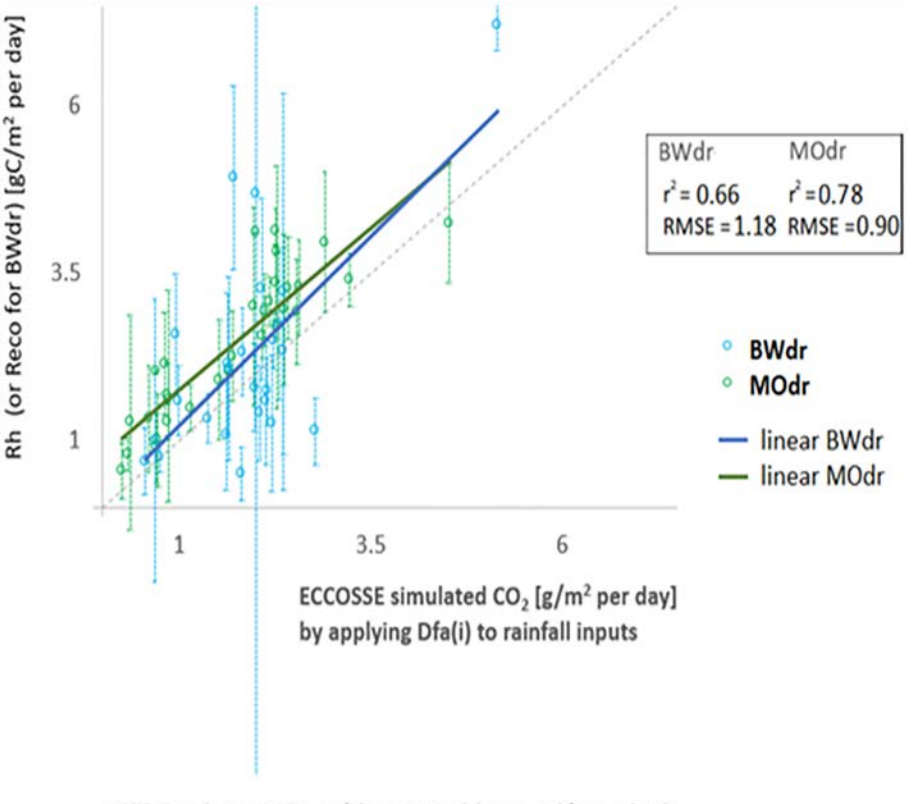


Figure 5.3. Measured water table (WT) and predicted water level (WL) from ECOSSE simulation runs with the application of drainage factor Dfa(*i*) at the Blackwater drained and Moyarwood drained sites. Adapted from Premrov *et al*. (2021); licensed under CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).



NOTE: Error bars are 95% confidence intrevals(computed from std.err);
some error bars are cut off due to zoomed-in scale

Figure 5.4. ECOSSE-simulated CO_2 versus measured heterotrophic respiration (Rh) for the Blackwater drained and Moyarwood drained sites, where the simulations were run by applying the drainage factor Dfa(*i*) to the rainfall inputs and by including long-term drainage periods. Note: $Rh = R_{eco}$ for non-vegetated Blackwater drained site. Adapted from Premrov *et al*. (2021); licensed under CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

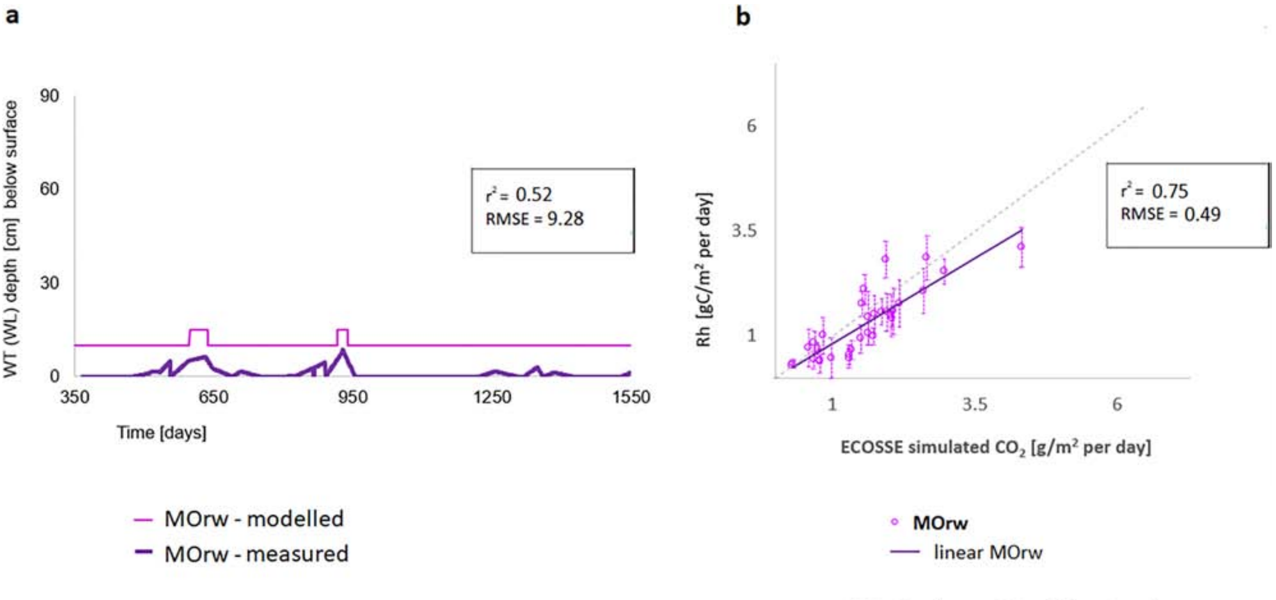
If the simulations were run without the inclusion of long-term drainage periods, high simulated CO_2 values occurred at the start of simulation, which resulted in an overestimation of predicted CO_2 fluxes. Therefore, the results indicated that running simulations that account for long-term drainage periods at drained peatland sites is recommended not only for modelling WLs, but also for modelling CO_2 fluxes, even when there is an absence of measured water table and climate data for previous years (i.e. during these periods without measurements, the long-term simulations were run by reusing the existing measured weather and water table data from later years).

5.4.3 Predicting water levels and CO_2 fluxes under drained to rewetted conditions

As explained previously, the simulation at the rewetted site was run by introducing a change in water table input from drained to rewetted conditions. The results showed that the simulation of WL change from drained to rewetted conditions was successful, although an overestimation in the simulated depth of WL (which refers to an underestimation in the rise of WL) under rewetted conditions was observed (Figure 5.5a). This result is in agreement with earlier ECOSSE modelling studies on cropland/arable soils, which indicates that the model does not correctly simulate the magnitude of changes in soil water content, although the model is capable of correctly simulating its trends, such as direction and timing (Flattery *et al*., 2018). Nevertheless, although the model performed less well in predicting WLs under rewetted conditions, the prediction of CO_2 emissions for MOrw was satisfactory, as is evident from the results of regression analysis of the modelled CO_2 fluxes and observed Rh (Figure 5.5b).

5.5 Conclusions on the Use of the ECOSSE Model

The use of the ECOSSE model with the improved water table simulation approach [by applying Dfa(*i*) and the inclusion of a long-term drainage period] successfully predicted WLs and CO_2 fluxes and their trends for the two peatland sites under drained conditions. For the rewetted site, the simulation was run under conditions from drained to rewetted, where the application of Dfa(*i*) was performed only during the long-term drainage period. The prediction of WLs for the rewetted period was less successful under rewetted conditions, which indicates a need for further



NOTE: Error bars are 95% confidence intrevals (computed from std.err)

Figure 5.5. ECOSSE-simulated outputs from the Moyarwood rewetted site: (a) simulated water level (WL) and observed water table (WT) (for the period under rewetted conditions); (b) simulated CO_2 fluxes versus measured heterotrophic respiration. Note: during the simulation run, drainage factor Dfa(*i*) was applied under drained conditions. Adapted from Premrov *et al*. (2021); licensed under CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

improvement of the water component in the ECOSSE model during rewetting. Despite this, the prediction of CO_2 fluxes at the rewetted site was successful. Overall, the results from the two Irish drained peatlands demonstrate that the application of Dfa(*i*) can improve model performance for the simulation of CO_2 fluxes, especially under drained conditions.

6 General Conclusions and Recommendations for Policymakers

6.1 Peat Properties

6.1.1 Heterogeneity of the national peatland resource

The properties of the peat soils encountered throughout Ireland in this survey were found to vary over a wide range, thereby confirming the pronounced diversity of peat types that are produced under unique conditions at individual sites. Our results demonstrate that peatland use and management have drastically altered peat properties on a very broad scale (from acute to limited change), compared with their "natural" counterparts. The main peatland LUCs in Ireland are grassland, forestry, cutaway (industrial extraction) and cutover (domestic extraction). The variations encountered among these LUCs reflect the nature and magnitude of the impacts of each use, with drainage intensity a key factor. The heterogeneity also presents difficulties in developing pedo-transfer functions for all possible combinations of peatland sites and LUCs. Regardless, the recognition of this heterogeneity, together with an understanding of the relationships between key edaphic and eco-hydrological properties, is critical for developing effective strategies for remedial management of degraded peatland ecosystems.

6.1.2 Overall status

Natural bogs were deeper than bogs in any other LUC but the difference was only statistically significant for raised bogs and mountain bogs, which suggests more intensive use of the more extensive lowland blanket bogs. The shallow depths under all LUCs indicate high rates of subsidence and loss of peat through organic matter decomposition, as well as peat removal through domestic and industrial extraction. The fewest discrepancies between natural and other LUC peat depths were measured in lowland blanket bogs, demonstrating their more extensive use.

Overall, shallower peat depth, greater bulk density and lower carbon content values characterise the degraded peat associated with managed peat soils. This was particularly the case for deep-drained grassland peat soils. In addition, mean nitrogen concentration values in the surface peat varied widely but did not differ across LUCs except for grassland, which consistently exhibited higher nitrogen concentrations. Overall, the nitrogen concentration (1.98%) in natural bogs did not differ significantly from the overall nitrogen concentrations across all LUCs (2.06%) but these values are much higher than the average value for north-western Europe (1.6% ± 0.4%) provided by, for example, Loisel *et al*. (2014), which reflects the widespread, intensive historical use of Irish peatlands.

6.1.3 Cutover bogs

The properties of the peat in cutover bogs differ the least from natural sites, displaying the same range in ash content but slightly higher bulk density values, which is indicative of the impact of drainage (to facilitate turf cutting). Despite their shallower peat depth, cutover peatlands hold the largest carbon store after undrained natural peatlands. These results indicate the importance of these degraded ecosystems in providing some critical ecosystem services. Therefore, they should be identified for immediate management interventions to prevent further degradation, particularly the ongoing loss of their carbon stores. For example, the drained area at Moyarwood was found to emit $5.2\,\mathrm{t\,CO_2\,ha^{-1}\,y^{-1}}$ over the 5-year monitoring period, in accordance with existing country-specific (IPCC Tier 2) emission factors from these domestic sites (Wilson *et al*., 2015).

6.1.4 Mountain blanket bogs

Our results confirm that, following drainage (regardless of use), changes in the physicochemical properties of peat occur, namely greater bulk density values, increased decomposition, and elevated pH and ash content. From a peatland type perspective, the greatest changes were encountered in mountain blanket bogs whose properties seem to be severely affected in both grassland and forestry land uses. This may be confounded by the fact that these LUCs occur mostly on shallower mountain blanket bogs. On the other hand, our results were surprising in that natural and cutover mountain blanket bogs displayed much greater peat depths than previously estimated. The lesser impact of domestic extraction may be only an artefact of the extensive rather than intensive activity on such sites. The datasets may have also been skewed towards mountain blanket bogs located at a lower elevation (highland mountain bog) rather than high-altitude sites where using the peat is rendered difficult.

6.1.5 Grasslands over peat

Deep-drained grassland peatlands were at the extreme end of the degradation scale encountered (compared with natural bogs) and they also contained the lowest organic matter and TOC contents. However, combined with greater bulk density values, this LUC comprises large SOC densities and contains a valuable carbon stock, despite the shallower peat. However, the high von Post values and elevated ash content make these peatlands very sensitive to continued organic matter decomposition and associated carbon losses.

6.2 Carbon Density

This study presented estimates of carbon densities for all bog types by LUC. These estimates support past studies (Table 6.1) for those categories that have typically (a) shallow peat depth and/or (b) a large number of measurements, such as cutaway peatland sites. New estimates for the cutover categories have proven to be revealing, as the carbon density is similar to natural bogs, which indicates that peat depth (so far not widely surveyed) is the most critical factor. The discrepancy with past studies is revealed, especially for mountain blanket bogs, which seem to have been underestimated in terms of both their depth and carbon content in previous studies. It is recommended that measuring peat depth in mountain blanket bogs is continued to confirm these results. A recent study on SOC in heavy textured grassland soils included an individual ombrotrophic peat soil which held 748 t C ha^{-1} while being on the shallow end of the range of peat depth in our study (116 cm) (Tuohy *et al*., 2021).

6.3 Carbon Stocks

The AUGER project assessed, for the first time, the total depth of peat at 270 sampling points across the breadth of peatland categories and types of management. Together with an updated areal extent of all peatland categories, we refined the estimates of carbon stock held in both natural and managed peatlands in Ireland, which we estimate to be 2216 Mt of carbon (uncertainty range: 2005–2320). This stock can be subdivided as follows: 42% in raised bogs, 42% in lowland blanket bogs and 15% in mountain blanket bogs. Remarkably, natural and cutover peatlands together hold just under half of the national peatland carbon stock. This new estimate is substantially higher than previous estimates, which ranged from 1071 Mt (Tomlinson, 2005) to 1469 Mt (Eaton *et al*., 2008), and is the result of (1) improved peat depth estimates, (2) improved peat carbon density values for mountain blanket bogs and (3) inclusion of all LUCs that occur on peat. Given that mineral soil carbon stocks have been estimated at *c*.1153 Mt for the 0–50 cm layer, which is the bulk of the store for these soils (Xu *et al*., 2011), peatlands store twice as much carbon and would thus represent two-thirds of the total national carbon stock.

Table 6.1. Comparison of carbon density (t C ha^{-1}) across studies for specific land use categories

Peatland type and LUC	This study	Eaton *et al.* (2008)	Tomlinson (2005)
Raised bog – natural	3037	4702	1025–3025
Raised bog – cutaway	1240	1179	495–1240
Raised bog – cutover	2398	1179	495–1240
Lowland blanket bog – natural	1409	1860	575–1440
Lowland blanket bog – cutaway	1396	1860	240–480
Mountain blanket bog – natural	1800	636	540
Mountain blanket bog – cutover	1248	636	270

6.4 Water Table Profiles

Our results confirm the high variability in hydrological regimes in all peatland types, including natural bogs, where different ontogenic development, peat properties and allogenic factors produce contrasting hydrological regimes both within and between sites. These relationships become even more complex in drained peatlands. While the groundwater table can be measured reliably in the field using piezometers and shallow monitoring wells, these point-based techniques are difficult to scale. Recent developments using Earth observation data (satellites or UAVs) have provided accurate models of groundwater levels, especially in open, treeless peatlands (Rahman *et al.*, 2017). This study also supports previous research, confirming the importance of the relationship between the water table and peat properties when rewetting peatlands, to inform sustainable engineering solutions on a site-by-site basis with a minimum of critical hydrological investigations.

Overall, the water table regime in blanket bogs seems to be sustained by constant precipitation, rendering them less sensitive to seasonal variation than raised bogs located in the Midlands, for example. However, this is predicated on the existing precipitation regime prevailing. Peat landslides are common throughout Ireland; in many cases their causes are multifaceted, involving weaknesses related to the nature of the peat cover (Boylan and Long, 2010), as well as hydrological and pedological associations with the underlying mineral substrates (Boylan *et al.*, 2008). While it has been suggested that upland peat slides are controlled by a slowly changing internal threshold and do not become more common during periods with an increased frequency of heavy precipitation events (Dykes *et al.*, 2008), how they will respond to additional climate change stress is of concern. The combination of drought followed by heavy rainfall events may add stress to these ecosystems, leading to increased risks of landslides. Moreover, human activities and management strategies further contribute to this risk. Further investigation of the hydrological regime of peatlands is critical in all scenarios.

The influence of forestry on water table drawdown is visible in all bog types but particularly in raised bogs. The findings of this study also support those of previous research that reported the importance of the relationship between the water table and peat properties, especially when rewetting cutover peatlands (Renou-Wilson *et al.*, 2018). However, this should be further investigated to inform sustainable engineering solutions. Successful “plumbing” of degraded bogs is the first critical step towards full recovery of all ecosystem functions.

It is recommended that, although monitoring of WTLs in natural/rewetted sites can be successfully achieved by a single logger, the spatial heterogeneity present in the other LUCs warrants the deployment of several loggers. Although the groundwater table can be measured reliably in the field using piezometers and shallow monitoring wells, these point-based techniques are difficult to scale up.

6.5 Vegetation Profiles

Reflecting the variety in peat properties, the vegetation profiles of Irish peatlands can be best characterised as heterogeneous, reinforcing the “each peatland site is unique” adage. Except for the extreme case of cutaway peatlands, where the vegetation is completely absent, the spatial patterns of vegetation communities are strong indicators of peatland type and conditions, which are unique to their location and to their management. Even grassland or forestry peatlands display a high level of heterogeneity between sites. The results also support the findings of previous studies that have demonstrated the importance of cutover bogs in providing biodiversity value, and confirm the successful outcomes of rewetting all types of managed drained peatlands (Renou-Wilson *et al.*, 2018, 2019).

The role of vegetation composition (or its absence) is central in determining the GHG dynamics of natural and managed peatlands (Renou-Wilson *et al.*, 2019). Certain assemblages (ecotopes) can be used as a proxy for the hydrological regime of a site and thus for predicting GHG dynamics (Regan *et al.*, 2020); however, the heterogeneity of vegetation composition (within and between sites), together with their associated local hydrological regimes, makes their inclusion in models to predict GHG dynamics difficult. The complexity of monitoring such spatial heterogeneity and attributing relative emission factors seems very high and can only be modelled using innovative methods. While the development of aerial imagery could help map these mosaic sites, certain barriers are still present, for instance overlapping spectral signatures of different vegetation communities or failure to recognise existing drainage systems.

6.6 Greenhouse Gas Emissions and Removals from Monitored Sites

This study demonstrated that long-term GHG monitoring can provide robust baseline datasets that can enable the effects of external and internal stressors to be appropriately evaluated in peatlands (Wilson *et al*., 2016b) and interannual variation to be suitably appraised. Such datasets contribute to Tiers 2 and 3 levels of reporting of GHG emissions for Ireland and highlight the key processes that are crucial for the future management of Irish peatlands:

- Drained peatlands are a substantial CO_2 source and a small CH_4 source.
- Rewetting at Moyarwood resulted in a sustained and elevated water level.
- Rewetting can rapidly transform carbon dynamics and switch a degraded peatland site to a net carbon sink.
- Under “normal” climatic years, annual NEE values at the rewetted Moyarwood site and the near-natural Clara bog site were similar.
- CH_4 emissions can increase substantially after rewetting and may remain elevated for at least 5 years.

In this study, we monitored a limited number of GHG sites which, given the high heterogeneity of peatlands demonstrated in this study, would indicate that further sites must be monitored across a wide geographical range.

6.7 ECOSSE Modelling with Improved Water Table Simulation Approach

In this study, the use of the ECOSSE model with the improved water table simulation approach successfully predicted WLs and CO_2 fluxes and their trends for the two drained peatland sites.

For the rewetted site, the simulation was run under conditions from drained to rewetted, where the application of the drainage factor [Dfa(*i*)] was performed only during the long-term drainage period. The prediction of WLs for the rewetted period was less successful under rewetted conditions, which indicates a need for further improvement of the water component in the ECOSSE model during rewetting. Despite this, the prediction of CO_2 fluxes at the Moyarwood rewetted site was successful. Overall, the results from the two Irish drained peatlands demonstrated that the application of the drainage factor can improve model performance for the simulation of CO_2 fluxes, especially under drained conditions.

The work presented here will make a positive contribution to the potential future development of Tier 3 methodology for estimating GHG emissions in peatlands, in terms of assessing the effect of different peatland LUCs/management practices using process-based modelling approaches. As these results demonstrate that using the ECOSSE model with the improved water table simulation approach could improve the model’s performance for the simulation of CO_2 fluxes, it is hoped that this will foster future process-based modelling studies of peatlands using the ECOSSE model to help understand the underlying factors and drivers influencing GHG emissions from managed peatlands.

The modelling work from this study provides insights into some of the potential research directions for future process-based modelling of GHG fluxes from managed peatlands. These include improving the model’s sensitivity in predicting WLs at depths of less than 5 cm, which may be important for modelling peatlands under rewetted conditions. This provides opportunities for further improvements and upgrading of the ECOSSE model in the future. In addition, further testing of the applicability of the developed drainage factor for peatlands that have undergone drainage, and for peatland types different from those at the sites used here, is also recommended. It is also recommended that the model’s uncertainty and sensitivity analysis should be investigated further. These potential additional studies are important for assessing the applicability of the drainage factor in process-based modelling studies of peatlands using the ECOSSE model.

6.8 Implications of New Datasets and Modelling for Policy Decisions and Future Research

- Regardless of their current land use, the heterogeneity of Irish peatland profiles must be fully recognised in future policy decisions about their ongoing management. This would also require full recognition of the importance of mapping peatlands to a level appropriate for their effective management.

- Each peatland exhibits unique properties with far-reaching implications for GHG production, cycling of carbon and nutrients, local and regional hydrology and water quality, and biodiversity. Therefore, "one-size-fits-all" management for rewetting bogs is not recommended. A minimum checklist of critical parameters must be compiled, and a toolbox must be developed and updated with feedback from the monitoring of current and existing peatland rewetting projects.
- Our new estimates of national peatland SOC stocks per LUC amount to a total of 2216 Mt of carbon (uncertainty range: 2005–2320 Mt). Natural and cutover bogs hold just over half of all of the SOC stored in Irish peatlands, which represent two-thirds of the national soil carbon stock. This has major implications for policy decisions and requires an urgent suite of actions to (1) ensure that these carbon stocks remain in the ground and (2) promote the development of carbon sinks in all types of land use.
- From an IPCC and GHG inventory reporting perspective, this study supports the need to obtain more accurate areal and GHG flux data from cutover bogs (private turbary),[13] as this is not accurately represented in the reporting of "managed" peatlands. Cutover bogs hold large carbon stocks that must be sustainably managed if Ireland wishes to meet its climate change targets.
- This project also demonstrated the critical need to continue the monitoring of GHG fluxes and associated environmental variables (WTLs and vegetation) given the diversity of conditions encountered in Ireland. The number of studies on drainage and rewetting impacts must be extended to include a wide range of site types and LUCs, with further categorisation according to their drainage depth (deep vs shallow), nutrient status and vegetation conditions. As different combinations of these factors may be present in a mosaic across a peatland site, new methods must also be developed to accurately map peatland habitats and associated properties (eco-hydrological mapping).
- The relatively high degree of uncertainty in current and future local hydro-meteorological variables should also be noted in the context of modelling peatland processes and peatland investigations (to inform planning).
- We have identified the following peatland LUCs for the establishment of long-term GHG monitoring capacity: grassland, domestic peat extraction and rewetting. Ideally, the monitoring of these sites should be aligned with the Integrated Carbon Observation System (ICOS) and would incorporate a combination of eddy covariance and chamber methodologies to fully capture GHG exchange at the micro and macro scales in the selected site.
- The use of process-orientated models is recommended by the IPCC for countries with a high proportion of peatlands to enable them to move to the Tier 3 reporting level with a reduction in associated uncertainty. Process models typically require a higher level of site parameter inputs than is used in empirical models; however, they provide a more reliable mechanism for predicting variability in GHG dynamics under future environmental and anthropogenic changes. Although we successfully improved the water table simulation approach in the ECOSSE model, and thus the prediction of CO_2 emissions from drained peat soils, the prediction of WTLs for the rewetted period was less successful under rewetted conditions. Further research on improving the water component in the ECOSSE model is essential, together with continuous empirical data collection (especially WTLs) from rewetted sites in particular. This is critical to support any sustainable peatland management schemes.
- The AUGER project has significantly augmented Irish peatland datasets, not only with edaphic and hydrological properties, carbon density and carbon stocks but also with water table regimes, vegetation profiles, GHG fluxes and carbon balances, thereby giving further insights into the biogeochemical processes that operate in these multifaceted ecosystems. The project has narrowed the gap between the various research communities working on peat soils, and

---

[13] "Private turbary" is the term used to describe the right to cut turf on a particular area of the bog.

it is hoped that the findings from this project will provide a basis for and a step towards an Irish peatland dataset hub for future collaborative research on peatlands. This project should also represent a step towards standardised multiscale measurements of peatland properties and thus enhance collaboration between empiricists and modellers to better advance peatland science.

References

Bousquet, P., Ciais, P., Miller, J.B., Dlugokencky, E.J., Hauglustaine, D.A., Prigent, C., Van der Werf, G.R., Peylin, P., Brunke, E.G., Carouge, C. *et al*., 2006. Contribution of anthropogenic and natural sources to atmospheric methane variability. *Nature* 443: 439–443.

Boylan, N. and Long, M., 2010. An investigation into peat slope failures in the Wicklow Mountains. *Biology and Environment Proceedings of the Royal Irish Academy* 110B: 173–184.

Boylan, N., Long, M. and Jennings, P., 2008. Peat slope failures in Ireland and the assessment of peat stability. *Proceedings 13th International Peat Congress: After Wise Use: The Future of Peatlands*, International Peatland Society, June, Tullamore, Co. Offaly, Ireland, pp. 665–670.

CCAC (Climate Change Advisory Council), 2020. *Annual Review 2020*. CCAC, Dublin.

Coleman, K. and Jenkinson, D.S., 1996. RothC-26.3 – A model for the turnover of carbon in soil. In Powlson, D.S., Smith, P., Smith, J.U. (eds), *Evaluation of Soil Organic Matter Models*. Springer, Berlin, Heidelberg, pp. 237–246.

Connolly, J., 2018. Mapping land use on Irish peatlands using medium resolution satellite imagery. *Irish Geography* 51: 187–204.

Connolly, J. and Holden, N.M., 2009. Mapping peat soils in Ireland: updating the derived Irish peat map. *Irish Geography* 42: 343–352.

Cushnan, H., 2018. Quantifying the baseline conditions and restoration potential of Irish raised bogs through hydrogeological and geophysical methods. PhD Thesis. Queen's University Belfast, Belfast, UK.

DECC (Department of the Environment, Climate and Communications), 2020. Cabinet approves €108 million funding for groundbreaking Bord na Móna bog rehabilitation plan. Available online: https://www.gov.ie/en/press-release/2aae1-cabinet-approves-108m-funding-for-groundbreaking-bord-na-mona-bog-rehabilitation-plan-minister-ryan-also-announces-that-47-more-projects-in-the-midlands-totalling-278m-are-approved-under-the-just-transition-fund/ (accessed 21 September 2021).

de Gruijter, J., Brus, D., Bierkens, M. and Knotters, M., 2006. *Sampling for Natural Resource Monitoring*. Springer, Berlin.

Donlan, J., O'Dwyer, J. and Byrne, K.A., 2016. Area estimations of cultivated organic soils in Ireland: reducing GHG reporting uncertainties. *Mires and Peat* 18: Article 1. https://doi.org/10.19189/MaP.2016.OMB.230

Duffy, P., Black, K., Fahey, D., Hyde, B., Kehoe, J., Murphy, B., Quirke, B., Ryan, A.M. and Ponzi, J., 2020. *Ireland's National Inventory Report 2020. Greenhouse Gas Emissions 1990-2018 Reported to the United Nations Framework Convention on Climate Change*. Environmental Protection Agency, Johnstown Castle, Ireland.

Dykes, A.P., Gunn, J. and Convery, K.J., 2008. Landslides in blanket peat on Cuilcagh Mountain, northwest Ireland. *Geomorphology* 102: 325–340.

Eaton, J.M., McGoff, N.M., Byrne, K.A., Leahy, P. and Kiely, G., 2008. Land cover change and soil organic carbon stocks in the Republic of Ireland 1851–2000. *Climatic Change* 91: 317–334.

Eglin, T., Ciais, P., Piao, S.L., Barre, P., Bellassen, V., Cadule, P., Chenu, C., Gasser, T., Koven, C., Reichstein, M. *et al*., 2010. Historical and future perspectives of global soil carbon response to climate and land-use changes. *Tellus B: Chemical and Physical Meteorology* 62: 700–718.

Eijkelkamp, 2005. *Operating Instructions: 04.09 Peat Sampler Set*. Giesbeek, Netherlands, p. 7.

EMEP (European Monitoring and Evaluation Programme), 2018. Data/EMEOP/2018_Reporting/Catalog. Meteorological Synthesizing Centre-West of EMEP, MET Norway Thredds Service, Norwegian Meteorological Institute. Available online from this website: https://erddap.ichec.ie/erddap/index.html (accessed April 2019).

EMEP (European Monitoring and Evaluation Programme), 2019. Old EMEP MSC-W modelled air concentrations and depositions: national totals and gridded data on html and ASCII format. Meteorological Synthesizing Centre-West of EMEP, Norwegian Meteorological Institute. Available online: http://www.emep.int/mscw/mscw_ydata.html (accessed 22 January 2019).

ERDDAP-ICHEC, 2019. EPA_Climate-WRF. ICHEC ERDDAP Server. ERDDAPv.1.82. Irish Centre for High-End Computing (ICHEC). Available online: https://erddap.ichec.ie/erddap/files/EPA_Climate/WRF/ (accessed 15 October 2021).

ESRI (Environmental Systems Research Institute), 2018. ArcGIS Desktop. ArcGIS 10.6.1. Environmental Systems Research Institute (ESRI), Inc., West Redlands, CA.

European Commission, 2019. *The EU Environmental Implementation Review Report – Ireland*. European Commission, Brussels. Available online: https://ec.europa.eu/environment/eir/pdf/report_ie_en.pdf (accessed December 2019).

European Union, 2018. Regulation (EU) 2018/841 of the European Parliament and of the Council of 30 May 2018 on the inclusion of greenhouse gas emissions and removals from land use, land use change and forestry in the 2030 climate and energy framework, and amending Regulation (EU) No 525/2013 and Decision No 529/2013/EU. OJ L 156, 19.06.2018, pp. 1–25.

European Union, 2020. The European Green Deal. European Parliament resolution of 15 January 2020 on the European Green Deal (2019/2956(RSP)). OJ C 270, 7.7.20, p. 2–20.

Fay, D., McGrath, D., Zhang, C., Carrigg, C., O’Flaherty, V., Carton, O.T. and Grennan, E., 2007. *Towards a National Soils Database (2001-CD-S2M2)*. Environmental Protection Agency, Johnstown Castle, Ireland.

Fealy, R., Green, S., Loftus, M., Meehan, R., Radford, T., Cronin, C. and Bulfin, M., 2009. *Teagasc EPA Soil and Subsoils Mapping Project – Final Report*. Volume I. Teagasc, Dublin.

Flattery, P., Fealy, R., Fealy, R.M., Lanigan, G. and Green, S., 2018. Simulation of soil carbon efflux from an arable soil using the ECOSSE model: need for an improved model evaluation framework? *Science of the Total Environment* 622–623: 1241–1249.

Forest Service, 2012. *The Second National Forest Inventory – Republic of Ireland – Main Findings.* Forest Service, Department of Agriculture, Food and the Marine, Johnstown Castle Estate, Ireland.

Frolking, S., Talbot, J., Jones, M.C., Treat, C.C., Kauffman, J.B., Tuittila, E.S. and Roulet, N., 2011. Peatlands in the Earth’s 21st century climate system. *Environmental Reviews* 19: 371–396.

Government of Ireland, 2021. Climate Action and Low Carbon Development (Amendment) Bill.

Green, S., 2020. Distribution of cultivated peats. Available online: https://www.teagasc.ie/rural-economy/rural-economy/spatial-analysis/gis-monthly-maps/2020-archive/#may20 (accessed May 2020).

Günther, A., Barthelmes, A., Huth, V., Joosten, H., Jurasinski, G., Koebsch, F. and Couwenberg, J., 2020. Prompt rewetting of drained peatlands reduces climate warming despite methane emissions. *Nature Communications* 11: 1644.

Hammond, R.F., 1981. *The Peatlands of Ireland*. Soil Survey Bulletin No. 35. An Foras Talúntais, Dublin.

Hardie, S.M.L., Garnett, M.H., Fallick, A.E., Ostle, N.J. and Rowland, A.P., 2009. Bomb-14C analysis of ecosystem respiration reveals that peatland vegetation facilitates release of old carbon. *Geoderma* 153: 393–401.

Helfter, C., Campbell, C., Dinsmore, K.J., Drewer, J., Coyle, M., Anderson, M., Skiba, U., Nemitz, E., Billett, M.F. *et al*., 2015. Drivers of long-term variability in CO_2 net ecosystem exchange in a temperate peatland. *Biogeosciences* 12: 1799–1811.

Huth, V., Günther, A., Jurasinski, G. and Glatzel, S., 2013. The effect of an exceptionally wet summer on methane effluxes from a 15-year re-wetted fen in north-east Germany. *Mires and Peat* 13: Article 2.

ICAO (International Civil Aviation Organisation), 2016. What would be the impact of a global MBM scheme for international aviation? Available online: https://www.icao.int/Meetings/HLM-MBM/Pages/FAQ3.aspx (accessed May 2020).

IPCC (Intergovernmental Panel on Climate Change), 2006. *IPCC Guidelines for National Greenhouse Gas Inventories*. Prepared by the National Greenhouse Gas Inventories Programme. Volume 4. Institute for Global Strategies, Kanagawa, Japan.

IPCC (Intergovernmental Panel on Climate Change), 2013. *Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Cambridge, UK, and New York, NY.

IPCC (Intergovernmental Panel on Climate Change), 2014. *2013 Supplement to the 2006 Intergovernmental Panel on Climate Change Guidelines for National Greenhouse Gas Inventories: Wetlands*. IPCC, Geneva, Switzerland.

Khalil, M., Kiely, G., O’Brien, P. and Müller, C., 2013. Organic carbon stocks in agricultural soils in Ireland using combined empirical and GIS approaches. *Geoderma* 193: 222–235.

Koehler, A.-K., Sottocornola, M. and Kiely, G., 2011. How strong is the current carbon sequestration of an Atlantic blanket bog? *Global Change Biology* 17: 309–319.

Liu, H. and Lennartz, B., 2019. Hydraulic properties of peat soils along a bulk density gradient – a meta study. *Hydrological Processes* 33: 101.

Loisel, J., Yu, Z., Beilman, D.W., Camill, P., Alm, J., Amesbury, M.J., Anderson, D., Andersson, S., Bochicchio, C., Barber, K. *et al*., 2014. A database and synthesis of northern peatland soil properties and Holocene carbon and nitrogen accumulation. *The Holocene* 24: 1028–1042.

Malone, S. and O'Connell, C., 2009. *Ireland's Peatland Conservation Action Plan 2020 – Halting the Loss of Biodiversity*. Irish Peatland Conservation Council, Dublin.

McVeigh, P., Sottocornola, M., Foley, N., Leahy, P. and Kiely, G., 2014. Meteorological and functional response partitioning to explain interannual variability of CO_2 exchange at an Irish Atlantic blanket bog. *Agricultural and Forest Meteorology* 194: 8–19.

Met Éireann, 2012. 30 year averages. The Irish Meteorological Service, Ireland. Available online: https://www.met.ie/climate/30-year-averages (accessed March 2019).

Minkkinen, K., Byrne, K.A. and Trettin, C., 2008. Climate impacts of peatland forestry. In Strack, M. (ed.), *Peatlands and Climate Change*. International Peat Society and Saarijärven Offset Oy, Saarijärvi, Finland, pp. 98–122.

Moncrieff, J.B., Massheder, J.M., de Bruin, H., Elbers, J., Friborg, T., Heusinkveld, B., Kabat, P., Scott, S., Soegaard, H. and Verhoef, A., 1997. A system to measure surface fluxes of momentum, sensible heat, water vapour and carbon dioxide. *Journal of Hydrology* 188–189: 589–611.

NPWS (National Parks and Wildlife Service), 2015. *National Peatlands Strategy*. Department of Arts, Heritage and the Gaeltacht, Dublin.

NPWS (National Parks and Wildlife Service), 2016. *National Raised Bog SAC Management Plan*. Department of Arts, Heritage and the Gaeltacht, Dublin.

Nugent, K.A., Strachan, I.B., Strack, M., Roulet, N.T. and Rochefort, L., 2018. Multi-year net ecosystem carbon balance of a restored peatland reveals a return to carbon sink. *Global Change Biology* 12: 5751–5768. https://doi.org/10.1111/gcb.14449.

Olander, L.P., Haugen-Kozyra, K., with contributions from Del Grosso, S., Izaurralde, C., Malin, D., Paustian, K. and Salas, W., 2011. *Using Biogeochemical Process Models to Quantify Greenhouse Gas Mitigation from Agricultural Management Projects.* Report NI R 11-03. Nicholas Institute for Environmental Policy Solutions, Duke University, Durham, NC.

Peters, W., Bastos, A., Ciais, P. and Vermeulen, A., 2020. A historical, geographical and ecological perspective on the 2018 European summer drought. *Philosophical Transactions of the Royal Society B: Biological Sciences* 375: 20190505.

Pitkänen, A., Turunen, J., Tahvanainen, T. and Simola, H., 2011. Comparison of different types of peat corers in volumetric sampling. *Suo-Mires and Peat* 62: 51–57.

Premrov, A., Zimmermann, J. and Saunders, M., 2019. Biogeochemical modelling of soil organic carbon-insights into the processing procedures of selected atmospheric input data: Part II-atmospheric nitrogen deposition from EMEP datasets. Poster presented at The 62nd Irish Geological Research Meeting, University College Dublin O'Brien Science Centre, Ireland. Available online: https://www.researchgate.net/publication/331480734_Biogeochemical_modelling_of_soil_organic_carbon-insights_into_the_processing_procedures_of_selected_atmospheric_input_data_Part_II-atmospheric_nitrogen_deposition_from_EMEP_datasets (accessed May 2019).

Premrov, A., Wilson, D., Saunders, M., Yeluripati, J. and Renou-Wilson, F., 2021. CO_2 fluxes from drained and rewetted peatlands using a new ECOSSE model water table simulation approach. *Science of the Total Environment* 754: 142433.

PSF (Python Software Foundation), 2017. Python 2.7.14. Available online: https://www.python.org/ (accessed March 2019).

R Core Team, 2019. R: A language and environment for statistical computing. R version 3.6.0. Foundation for Statistical Computing, Vienna, Austria. Available online: https://www.R-project.org/ (accessed March 2019).

Rahman, M.M., McDermid, G.J., Strack, M. and Lovitt, J., 2017. A new method to map groundwater table in peatlands using unmanned aerial vehicles. *Remote Sensing* 9: 1057.

Regan, S., Swenson, M.M., O'Connor, M. and Gill, A.L., 2020. *Ecoydrology, Greenhouse Gas Dynamics and Restoration Guidelines for Degraded Raised Bogs.* Environmental Protection Agency, Johnstown Castle, Ireland.

Renou-Wilson, F., Keane, M., McNally, G., O'Sullivan, J. and Farrell, E.P. 2008. *BOGFOR Programme Final Report: A Research Programme to Develop a Forest Resource on Industrial Cutaway Peatlands in the Irish Midlands*. COFORD, Dublin.

Renou-Wilson, F., Bolger, T., Bullock, C., Convery, F., Curry, J.P., Ward, S., Wilson, D. and Müller, C., 2011. *BOGLAND: Sustainable Management of Peatlands in Ireland*. STRIVE Report No. 75. Environmental Protection Agency, Johnstown Castle, Ireland.

Renou-Wilson, F., Barry, C., Müller, C. and Wilson, D., 2014. The impacts of drainage, nutrient status and management practice on the full carbon balance of grasslands on organic soils in a maritime temperate zone. *Biogeosciences* 11: 4361–4379.

Renou-Wilson, F., Müller, C., Moser, G. and Wilson, D., 2016. To graze or not to graze? Four years greenhouse gas balances and vegetation composition from a drained and a rewetted organic soil under grassland. *Agriculture, Ecosystems & Environment* 222: 156–170.

Renou-Wilson, F., Wilson, D., Rigney, C., Byrne, K., Farrell, C. and Müller, C., 2018. *Network Monitoring Rewetted and Restored Peatlands/Organic Soils for Climate and Biodiversity Benefits (NEROS Project Synthesis Report)*. EPA Research Report No 236. Environmental Protection Agency, Johnstown Castle, Ireland.

Renou-Wilson, F., Moser, G., Fallon, D., Farrell, C.A., Müller, C. and Wilson, D., 2019. Rewetting degraded peatlands for climate and biodiversity benefits: results from two raised bogs. *Ecological Engineering* 127: 547–560.

Saunois, M., Stavert, A.R., Poulter, B., Bousquet, P., Canadell, J.G., Jackson, R.B., Raymond, P.A., Dlugokencky, E.J., Houweling, S., Patra, P.K. *et al*., 2020. The Global Methane Budget 2000–2017. *Earth System Science Data* 12: 1561–1623.

Schouten, M.G.C. (ed.), 2002. *Conservation and Restoration of Raised Bogs: Geological, Hydrological and Ecological Studies.* Department of the Environmental and Local Government, Staatsbosbeheer, Netherlands.

Simo, I., Creamer, R., O'Sullivan, L., Reidy, B., Schulte, R. and Fealy, R., 2014. *Irish Soil Information System: Soil Property Maps*. Environmental Protection Agency, Johnstown Castle, Ireland.

Smith, J., Gottschalk, P., Bellarby, J., Richards, M., Nayak, D., Coleman, K., Hiller, J., Flynn, H., Wattenbach, M., Aitkenhead, M. *et al*., 2010. *Model to Estimate Carbon in Organic Soils – Sequestration and Emissions (ECOSSE). User Manual.* Available online: https://www.abdn.ac.uk/staffpages/uploads/soi450/ECOSSE%20User%20manual%20310810.pdf (accessed March 2019).

Smith, J.U., Bradbury, N.J. and Addiscott, T.M., 1996. SUNDIAL: a PC-based system for simulating nitrogen dynamics in arable land. *Agronomy Journal* 88: 38–43.

Thornthwaite, C.W., 1948. An approach toward a rational classification of climate. *Geographical Review* 38: 55–94.

Tiemeyer, B., Freibauer, A., Borraz, E.A., Augustin, J., Bechtold, M., Beetz, S., Beyer, C., Ebli, M., Eickenscheidt, T., Fiedler, S. *et al*., 2020. A new methodology for organic soils in national greenhouse gas inventories: data synthesis, derivation and application. *Ecological Indicators* 109: 105838.

Tomlinson, R.W., 2005. Soil carbon stocks and changes in the Republic of Ireland. *Journal of Environmental Management* 76: 77–93.

Tuittila, E.-S., Komulainen, V.-M., Vasander, H. and Laine, J., 1999. Restored cut-away peatland as a sink for atmospheric CO_2. *Oecologia* 120: 563–574.

Tuohy, P., O'Sullivan, L. and Fenton, O., 2021. Field scale estimates of soil carbon stocks on ten heavy textured farms across Ireland. *Journal of Environmental Management* 281: 111903.

Urbanová, Z. and Bárta, J., 2020. Recovery of methanogenic community and its activity in long-term drained peatlands after rewetting. *Ecological Engineering* 150: 105852.

van Breemen, N., 1995. How *Sphagnum* bogs down other plants. *Trends in Ecology & Evolution* 10: 270–275.

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. *Ecoscience* 14: 71–80.

Wilson, D., Alm, J., Laine, J., Byrne, K.A., Farrell, E.P. and Tuittila, E.-S., 2009. Rewetting of cutaway peatlands: are we re-creating hotspots of methane emissions? *Restoration Ecology* 17: 796–806.

Wilson, D., Müller, C. and Renou-Wilson, F., 2013a. Carbon emissions and removals from Irish peatlands: current trends and future mitigation measures. *Irish Geography* 46: 1–23.

Wilson, D., Farrell, C., Müller, C., Hepp, S. and Renou-Wilson, F., 2013b. Rewetted industrial cutaway peatlands in western Ireland: prime location for climate change mitigation? *Mires and Peat* 11: Article 1, 1–22.

Wilson, D., Dixon, S.D., Artz, R.R.E., Smith, T.E.L., Evans, C.D., Owen, H.J.F., Archer, E. and Renou-Wilson, F., 2015. Derivation of greenhouse gas emission factors for peatlands managed for extraction in the Republic of Ireland and the United Kingdom. *Biogeosciences* 12: 5291–5308.

Wilson, D., Blain, D., Couwenberg, J., Evans, C.D., Murdiyarso, D., Page, S., Renou-Wilson, F., Rieley, J., Sirin, A., Strack, M. *et al*., 2016a. Greenhouse gas emission factors associated with rewetting of organic soils. *Mires and Peat* 17(Article 4): 1–28.

Wilson, D., Farrell, C., Fallon, D., Moser, G., Muller, C. and Renou-Wilson, F., 2016b. Multi-year greenhouse gas balances at a rewetted temperate peatland. *Global Change Biology* 22: 4080–4095.

Xu, J., Morris, P.J., Liu, J. and Holden, J., 2018. PEATMAP: refining estimates of global peatland distribution based on a meta-analysis. *Catena* 160: 134–140.

Xu, X., Liu, W., Zhang, C. and Kiely, G., 2011. Estimation of soil organic carbon stock and its spatial distribution in the Republic of Ireland. *Soil Use and Management* 27: 156–162.

Abbreviations

BD	Bulk density
BWdr	Blackwater, drained
Dfa	Drainage factor
DOC	Dissolved organic carbon
GHG	Greenhouse gas
GPP	Gross primary production
IPCC	Intergovernmental Panel on Climate Change
LUC	Land use category
LULUCF	Land use, land use change and forestry
MOdr	Moyarwood, drained
MOrw	Moyarwood, rewetted
NECB	Net ecosystem carbon balance
NEE	Net ecosystem exchange
$\mathbf{NEE}_{\mathbf{GS}}$	Growing season net ecosystem exchange
R_{eco}	Ecosystem respiration
Rh	Heterotrophic respiration
RMSE	Root mean square error
SOC	Soil organic carbon
TOC	Total organic carbon
UAV	Unmanned aerial vehicle
WL	Water level
WTL	Water table level

Appendix 1 Statistical Distribution of Soil Properties across Peatland Types and Land Use Categories

The statistical distribution of soil properties of the upper layer (0–10 cm) across peatland type and LUCs are shown in the following tables. For each table: Q25, 25th quantile; Q75, 75th quantile, lower CI, lower bound of confidence interval (alpha = 0.05) and upper CI, upper bound of confidence interval (alpha = 0.05).

Table A1.1. Peat depth (cm)

Peatland type	Land use category	Mean	Min.	Max.	Median	Q25	Q75	Lower CI	Upper CI	*n*
Raised bog	Natural	690	520	870	660	610	800	620	760	14
	Forestry	240	30	540	220	190	260	190	280	28
	Grassland	100	30	290	70	40	160	70	140	22
	Cutover	350	200	500	350	270	440	310	390	23
	Cutaway	140	50	260	140	130	160	130	160	30
Lowland blanket bog	Natural	270	150	420	270	230	290	240	300	17
	Forestry	190	60	340	190	100	280	150	240	24
	Grassland	140	50	320	150	80	200	110	170	21
	Cutover	220	100	340	210	170	270	180	260	17
	Cutaway	120	40	280	100	50	180	70	170	12
Mountain blanket bog	Natural	340	130	590	390	180	460	250	440	14
	Forestry	60	30	110	50	40	70	40	70	18
	Grassland	110	30	210	110	50	150	70	150	12
	Cutover	160	30	300	20	140	180	120	190	18

Table A1.2. pH

Peatland type	Land use category	Mean	Min.	Max.	Median	Q25	Q75	Lower CI	Upper CI	*n*
Raised bog	Natural	4.3	4.1	4.6	4.3	4.2	4.3	4.2	4.4	14
	Forestry	4.4	3.6	5.9	4.2	4	4.4	4.1	4.6	28
	Grassland	5.9	4.1	7.1	6.3	5.4	6.5	5.5	6.3	22
	Cutover	4.2	3.9	4.5	4.2	4.1	4.3	4.1	4.3	23
	Cutaway	5.3	4.2	6.8	5.2	4.5	6	5	5.6	30
Lowland blanket bog	Natural	4.6	4.4	5.0	4.6	4.5	4.6	4.5	4.7	17
	Forestry	4.4	3.9	4.7	4.4	4.3	4.6	4.3	4.5	24
	Grassland	4.7	4.1	5.3	4.8	4.4	5.0	4.6	4.9	21
	Cutover	4.3	3.9	4.6	4.3	4.2	4.4	4.2	4.4	17
	Cutaway	4.5	3.9	4.8	4.5	4.3	4.7	4.3	4.6	12
Mountain blanket bog	Natural	4.1	3.6	4.7	4.2	3.7	4.5	3.9	4.4	14
	Forestry	4.9	4.0	6.6	4.5	4.2	5.5	4.4	5.3	18
	Grassland	4.8	4.5	5.1	4.8	4.6	5.1	4.7	5	12
	Cutover	4.2	3.8	4.6	4.3	4.1	4.4	4.1	4.3	18

Table A1.3. Bulk density values (g cm^{-3})

Peatland type	Land use category	Mean	Min.	Max.	Median	Q25	Q75	Lower CI	Upper CI	*n*
Raised bog	Natural	0.07	0.02	0.11	0.07	0.06	0.10	0.06	0.09	14
	Forestry	0.14	0.03	0.24	0.14	0.11	0.19	0.12	0.17	28
	Grassland	0.33	0.17	0.67	0.33	0.23	0.39	0.28	0.39	22
	Cutover	0.13	0.05	0.24	0.13	0.11	0.17	0.12	0.16	23
	Cutaway	0.18	0.09	0.32	0.18	0.17	0.21	0.17	0.20	30
Lowland blanket bog	Natural	0.05	0.01	0.12	0.05	0.03	0.06	0.04	0.07	17
	Forestry	0.07	0.05	0.10	0.07	0.06	0.08	0.06	0.08	24
	Grassland	0.18	0.05	0.60	0.18	0.09	0.33	0.15	0.28	21
	Cutover	0.12	0.06	0.20	0.12	0.09	0.16	0.11	0.15	17
	Cutaway	0.17	0.10	0.20	0.17	0.13	0.18	0.14	0.18	12
Mountain blanket bog	Natural	0.06	0.03	0.10	0.06	0.05	0.09	0.05	0.08	14
	Forestry	0.14	0.03	0.80	0.14	0.10	0.18	0.09	0.25	18
	Grassland	0.09	0.04	0.15	0.09	0.07	0.13	0.07	0.12	12
	Cutover	0.13	0.07	0.22	0.13	0.11	0.15	0.11	0.15	18

Table A1.4. Organic matter content (%)

Peatland type	Land use category	Mean	Min.	Max.	Median	Q25	Q75	Lower CI	Upper CI	*n*
Raised bog	Natural	96.36	94.81	97.83	96.5	95.93	96.92	95.85	96.86	14
	Forestry	93.24	77.54	98.43	95.67	92.82	96.86	90.93	95.55	28
	Grassland	71.65	29.71	93.96	77.56	57.95	85.98	63.19	80.11	22
	Cutover	96.67	93.83	98.44	97.04	95.81	97.36	96.15	97.2	23
	Cutaway	92.52	85.77	98.65	92.27	87.63	97.04	90.83	94.22	30
Lowland blanket bog	Natural	97.05	96.05	98.05	96.97	96.81	97.32	96.82	97.29	17
	Forestry	96.77	92.29	98.42	97.12	96.11	97.67	96.16	97.39	24
	Grassland	76.27	24.80	97.39	94.57	52.75	96.06	64.83	87.71	21
	Cutover	97.08	93.74	98.19	97.25	96.86	97.65	96.54	97.62	17
	Cutaway	95.16	88.57	97.99	95.44	94.76	96.42	93.59	96.74	12
Mountain blanket bog	Natural	96.79	95.58	98.39	96.77	96.14	97.1	96.32	97.25	14
	Forestry	72.84	20.69	97.52	81.92	52.13	93.70	60.24	85.43	18
	Grassland	89.1	62.79	96.89	92.27	86.85	96.51	82.6	95.59	12
	Cutover	93.02	34.06	97.8	96.65	96.14	97.02	85.69	100.34	18

Table A1.5. Total organic carbon content (%)

Peatland type	Land use category	Mean	Min.	Max.	Median	Q25	Q75	Lower CI	Upper CI	*n*
Raised bog	Natural	51.59	50.78	52.24	51.7	50.9	52.15	51.21	51.96	14
	Forestry	53.11	49.41	56.06	53.45	52.36	54.14	52.28	53.93	28
	Grassland	40.64	24.81	49.6	41.61	29.01	49.53	36.00	45.29	22
	Cutover	53.44	52.29	54.38	53.54	52.32	54.09	53.05	53.82	23
	Cutaway	54.72	51.48	58.27	55.38	52.36	56.09	53.77	55.66	30
Lowland blanket bog	Natural	51.80	51.44	52.35	51.56	51.44	52.35	51.59	52.02	17
	Forestry	52.91	52.75	53.17	52.87	52.77	53.01	52.84	52.99	24
	Grassland	41.26	25.94	52.23	51.22	25.94	52.23	35.58	46.93	21
	Cutover	54.14	52.38	56.22	53.74	52.38	56.22	53.27	55.00	17
	Cutaway	58.11	57.89	58.32	58.11	57.89	58.32	57.96	58.25	12
Mountain blanket bog	Natural	52.79	51.54	53.34	53.21	51.96	53.34	52.31	53.26	14
	Forestry	39.74	28.05	51.60	39.57	28.05	51.60	34.82	44.66	18
	Grassland	46.77	45.96	47.58	46.77	45.96	47.58	46.23	47.31	12
	Cutover	54.06	52.9	54.83	54.46	52.9	54.83	53.64	54.49	18

Table A1.6. Nitrogen content (%)

Peatland type	Land use category	Mean	Min.	Max.	Median	Q25	Q75	Lower CI	Upper CI	*n*
Raised bog	Natural	2.04	1.59	2.32	2.18	1.73	2.2	1.87	2.22	14
	Forestry	2.06	1.49	2.65	2.09	1.58	2.52	1.88	2.25	28
	Grassland	2.48	1.99	3.01	2.46	2.04	2.93	2.29	2.67	22
	Cutover	1.83	1.68	1.99	1.82	1.78	1.87	1.79	1.87	23
	Cutaway	1.96	1.24	2.42	1.97	1.75	2.4	1.79	2.12	30
Lowland blanket bog	Natural	1.91	1.83	2.09	1.85	1.83	2.09	1.85	1.97	17
	Forestry	1.93	1.53	2.72	1.73	1.62	2.04	1.73	2.13	24
	Grassland	2.03	1.88	2.24	1.95	1.88	2.24	1.96	2.10	21
	Cutover	2.17	1.80	2.48	2.25	1.80	2.48	2.02	2.33	17
	Cutaway	1.62	1.34	1.91	1.62	1.34	1.91	1.44	1.81	12
Mountain blanket bog	Natural	2.01	1.61	2.22	2.1	1.73	2.22	1.86	2.17	14
	Forestry	1.77	1.50	1.97	1.83	1.50	1.97	1.67	1.87	18
	Grassland	2.55	2.25	2.85	2.55	2.25	2.85	2.35	2.75	12
	Cutover	2.31	2.04	2.56	2.34	2.04	2.56	2.2	2.42	18

Table A1.7. Gravimetric water content (%)

Peatland type	Land use category	Mean	Min.	Max.	Median	Q25	Q75	Lower CI	Upper CI	*n*
Raised bog	Natural	91.9	87.1	94.8	92.1	91.2	92.9	90.9	92.9	14
	Forestry	73.2	45	90.8	70.8	66.8	82.1	68.8	77.7	28
	Grassland	63	42.8	82.6	61.6	55	65.6	57.8	68.2	22
	Cutover	85.6	75.2	95.2	85	83.9	88.2	83.7	87.5	23
	Cutaway	79.8	68.9	90.4	80.6	76.3	83.8	77.7	81.9	30
Lowland blanket bog	Natural	92.2	88.6	94.6	92.5	90.7	93.7	91.2	93.2	17
	Forestry	86.0	64.3	94.0	88.7	86.6	90.6	82.5	89.5	24
	Grassland	77.8	49.3	90.7	82.4	67.1	88.0	72.3	83.3	21
	Cutover	87.5	80.8	93.1	87.8	83.7	91.2	85.4	89.6	17
	Cutaway	84.7	82.7	89.1	84.4	83.7	85.2	83.6	85.8	12
Mountain blanket bog	Natural	91.9	88.8	94.9	91.7	91.1	93.1	91.0	92.8	14
	Forestry	81.4	50.5	91.8	83.8	79.3	86.3	76.8	86.1	18
	Grassland	86.8	80.4	91.5	86.6	85.9	88.1	85.1	88.6	12
	Cutover	86	63.9	92	86.7	85.9	88.9	83.1	89	18

Table A1.8. Volumetric water content (%)

Peatland type	Land use category	Mean	Min.	Max.	Median	Q25	Q75	Lower CI	Upper CI	*n*
Raised bog	Natural	84.8	32.9	118.7	84	75.2	101.4	71.8	97.8	14
	Forestry	49.7	4.2	98.9	40.4	31.6	75.6	38.6	60.8	28
	Grassland	57.6	29.8	85.7	57.5	43.7	64.3	50.1	65	22
	Cutover	83.3	50.8	106.3	88.5	70.3	95.7	76.2	90.4	23
	Cutaway	76.4	45	107.8	73.3	63.6	92.4	69.3	83.6	30
Lowland blanket bog	Natural	62.6	21.2	95.8	58.6	46.2	77.3	51.0	74.2	17
	Forestry	53.7	11.7	99.3	56.7	38.0	71.5	43.8	63.7	24
	Grassland	68.5	44.1	97.8	73.3	57.1	74.9	61.9	75.2	21
	Cutover	90.7	69.0	107.7	92.6	84.0	98.7	84.9	96.5	17
	Cutaway	88.5	56.5	110.8	89.0	82.1	101.7	77.2	99.7	12
Mountain blanket bog	Natural	71	43.6	102	68.9	58.8	82	59.9	82.1	14
	Forestry	66.0	18.3	94.4	71.1	45.9	85.8	54.3	77.8	18
	Grassland	60.4	34.5	87.6	59	53.6	72.3	50.2	70.7	12
	Cutover	85.7	39.1	120.8	89.3	77.1	98.1	75.2	96.1	18

Appendix 2 Chemical Properties Down the Peat Profile

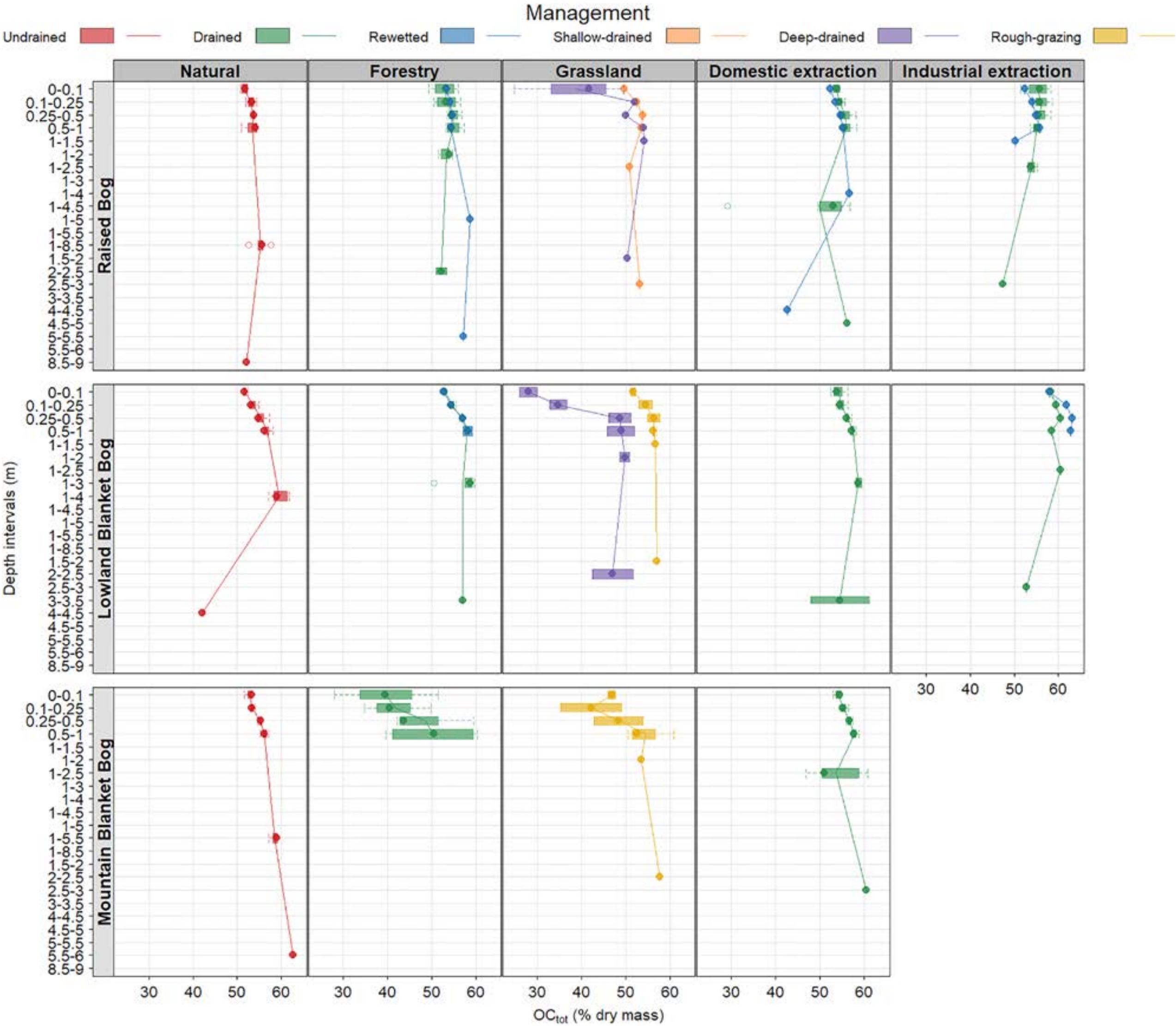


Figure A2.1. Distribution of total organic carbon (%) values along the depth gradient for combinations of peatland type (raised bog, lowland blanket bog, mountain blanket bog) and land use category [natural, forestry, grassland, cutover (domestic extraction) and cutaway (industrial extraction)]. Depth intervals (m) are connected through an average line. Colour box plots with error bars depict each peatland type–land use category combination across management options (undrained, drained, rewetted, shallow drained, deep drained, and rough grazing only for grassland).

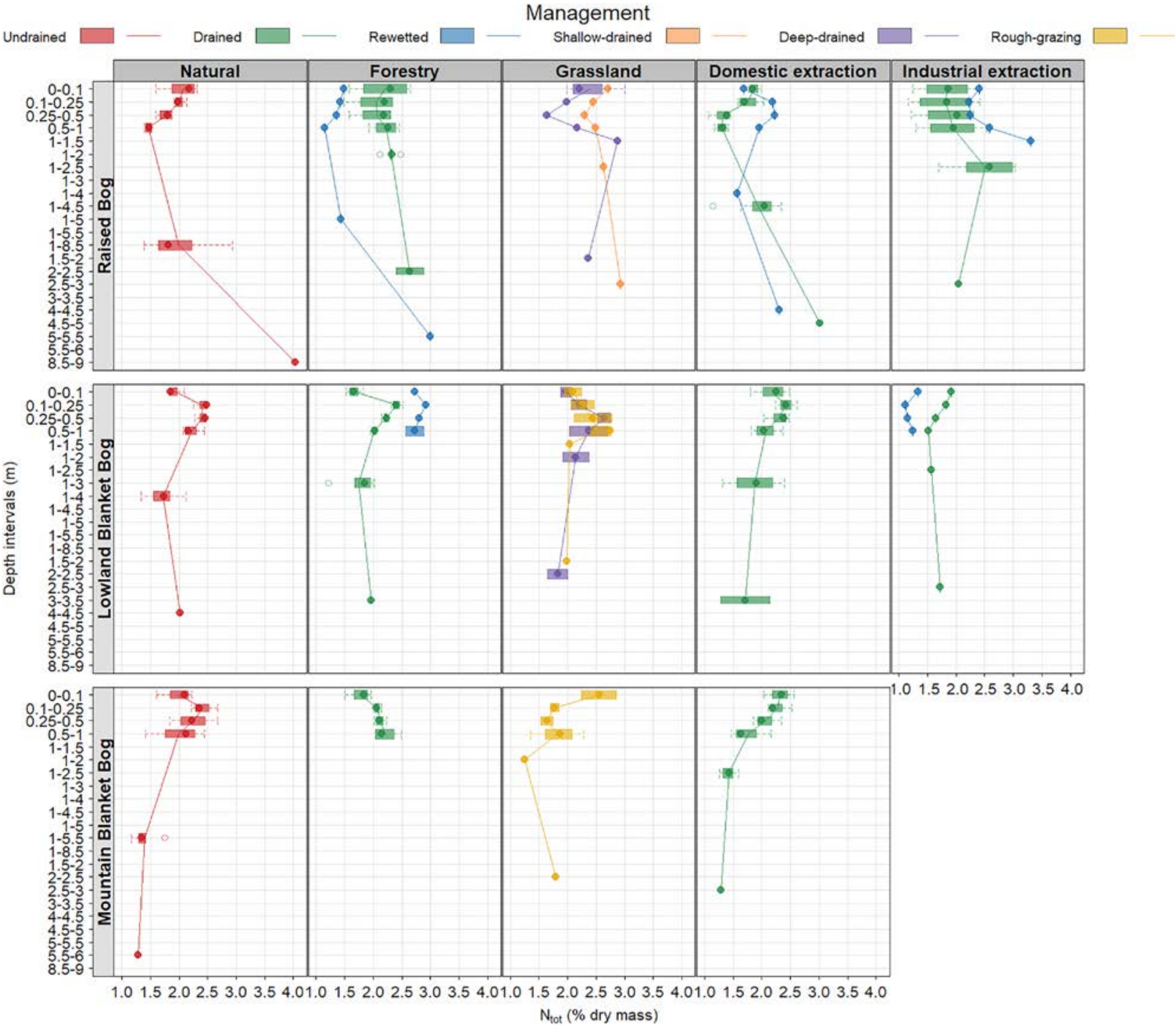


Figure A2.2. Distribution of nitrogen (%) values along depth gradient for combinations of peatland type (vertical: raised bog, lowland blanket bog, mountain blanket bog) – land use [horizontal: natural, forest, grassland, cutover (domestic extraction), and cutaway (industrial extraction)]. Depth intervals (m) are connected through an average-line. Colour box plots with error bars depicts each peatland type – land use category combination across management options (undrained, drained, rewetted, shallow-drained, deep drained, and rough grazing only for grassland).

AN GHNÍOMHAIREACHT UM CHAOMHNÚ COMHSHAOIL
Tá an Ghníomhaireacht um Chaomhnú Comhshaoil (GCC) freagrach as an gcomhshaol a chaomhnú agus a fheabhsú mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ó éifeachtaí díobhálacha na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialú: *Déanaimid córais éifeachtacha rialaithe agus comhlíonta comhshaoil a chur i bhfeidhm chun torthaí maithe comhshaoil a sholáthar agus chun díriú orthu siúd nach gcloíonn leis na córais sin.*

Eolas: *Soláthraímid sonraí, faisnéis agus measúnú comhshaoil atá ar ardchaighdeán, spriocdhírithe agus tráthúil chun bonn eolais a chur faoin gcinnteoireacht ar gach leibhéal.*

Tacaíocht: *Bímid ag saothrú i gcomhar le grúpaí eile chun tacú le comhshaol atá glan, táirgiúil agus cosanta go maith, agus le hiompar a chuirfidh le comhshaol inbhuanaithe.*

Ár bhFreagrachtaí

Ceadúnú

Déanaimid na gníomhaíochtaí seo a leanas a rialú ionas nach ndéanann siad dochar do shláinte an phobail ná don chomhshaol:

- saoráidí dramhaíola *(m.sh. láithreáin líonta talún, loisceoirí, stáisiúin aistrithe dramhaíola)*;
- gníomhaíochtaí tionsclaíocha ar scála mór *(m.sh. déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta)*;
- an diantalmhaíocht *(m.sh. muca, éanlaith)*;
- úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe *(OGM)*;
- foinsí radaíochta ianúcháin *(m.sh. trealamh x-gha agus radaiteiripe, foinsí tionsclaíocha)*;
- áiseanna móra stórála peitril;
- scardadh dramhuisce;
- gníomhaíochtaí dumpála ar farraige.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil

- Clár náisiúnta iniúchtaí agus cigireachtaí a dhéanamh gach bliain ar shaoráidí a bhfuil ceadúnas ón nGníomhaireacht acu.
- Maoirseacht a dhéanamh ar fhreagrachtaí cosanta comhshaoil na n-údarás áitiúil.
- Caighdeán an uisce óil, arna sholáthar ag soláthraithe uisce phoiblí, a mhaoirsiú.
- Obair le húdaráis áitiúla agus le gníomhaireachtaí eile chun dul i ngleic le coireanna comhshaoil trí chomhordú a dhéanamh ar líonra forfheidhmiúcháin náisiúnta, trí dhíriú ar chiontóirí, agus trí mhaoirsiú a dhéanamh ar leasúchán.
- Cur i bhfeidhm rialachán ar nós na Rialachán um Dhramhthrealamh Leictreach agus Leictreonach (DTLL), um Shrian ar Shubstaintí Guaiseacha agus na Rialachán um rialú ar shubstaintí a ídíonn an ciseal ózóin.
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Uisce

- Monatóireacht agus tuairisciú a dhéanamh ar cháilíocht aibhneacha, lochanna, uiscí idirchriosacha agus cósta na hÉireann, agus screamhuiscí; leibhéil uisce agus sruthanna aibhneacha a thomhas.
- Comhordú náisiúnta agus maoirsiú a dhéanamh ar an gCreat-Treoir Uisce.
- Monatóireacht agus tuairisciú a dhéanamh ar Cháilíocht an Uisce Snámha.

Monatóireacht, Anailís agus Tuairisciú ar an gComhshaol

- Monatóireacht a dhéanamh ar cháilíocht an aeir agus Treoir an AE maidir le hAer Glan don Eoraip (CAFÉ) a chur chun feidhme.
- Tuairisciú neamhspleách le cabhrú le cinnteoireacht an rialtais náisiúnta agus na n-údarás áitiúil *(m.sh. tuairisciú tréimhsiúil ar staid Chomhshaol na hÉireann agus Tuarascálacha ar Tháscairí)*.

Rialú Astaíochtaí na nGás Ceaptha Teasa in Éirinn

- Fardail agus réamh-mheastacháin na hÉireann maidir le gáis cheaptha teasa a ullmhú.
- An Treoir maidir le Trádáil Astaíochtaí a chur chun feidhme i gcomhair breis agus 100 de na táirgeoirí dé-ocsaíde carbóin is mó in Éirinn.

Taighde agus Forbairt Comhshaoil

- Taighde comhshaoil a chistiú chun brúnna a shainaithint, bonn eolais a chur faoi bheartais, agus réitigh a sholáthar i réimsí na haeráide, an uisce agus na hinbhuanaitheachta.

Measúnacht Straitéiseach Timpeallachta

- Measúnacht a dhéanamh ar thionchar pleananna agus clár beartaithe ar an gcomhshaol in Éirinn *(m.sh. mórphleananna forbartha)*.

Cosaint Raideolaíoch

- Monatóireacht a dhéanamh ar leibhéil radaíochta, measúnacht a dhéanamh ar nochtadh mhuintir na hÉireann don radaíocht ianúcháin.
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha.
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta.
- Sainseirbhísí cosanta ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Faisnéis Inrochtana agus Oideachas

- Comhairle agus treoir a chur ar fáil d'earnáil na tionsclaíochta agus don phobal maidir le hábhair a bhaineann le caomhnú an chomhshaoil agus leis an gcosaint raideolaíoch.
- Faisnéis thráthúil ar an gcomhshaol ar a bhfuil fáil éasca a chur ar fáil chun rannpháirtíocht an phobail a spreagadh sa chinnteoireacht i ndáil leis an gcomhshaol *(m.sh. Timpeall an Tí, léarscáileanna radóin)*.
- Comhairle a chur ar fáil don Rialtas maidir le hábhair a bhaineann leis an tsábháilteacht raideolaíoch agus le cúrsaí práinnfhreagartha.
- Plean Náisiúnta Bainistíochta Dramhaíola Guaisí a fhorbairt chun dramhaíl ghuaiseach a chosc agus a bhainistiú.

Múscailt Feasachta agus Athrú Iompraíochta

- Feasacht chomhshaoil níos fearr a ghiniúint agus dul i bhfeidhm ar athrú iompraíochta dearfach trí thacú le gnóthais, le pobail agus le teaghlaigh a bheith níos éifeachtúla ar acmhainní.
- Tástáil le haghaidh radóin a chur chun cinn i dtithe agus in ionaid oibre, agus gníomhartha leasúcháin a spreagadh nuair is gá.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil

Tá an ghníomhaíocht á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóirí. Déantar an obair ar fud cúig cinn d'Oifigí:

- An Oifig um Inmharthanacht Comhshaoil
- An Oifig Forfheidhmithe i leith cúrsaí Comhshaoil
- An Oifig um Fianaise is Measúnú
- Oifig um Chosaint Radaíochta agus Monatóireachta Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag comhaltaí air agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

EPA Research Report 401

Peatland Properties Influencing Greenhouse Gas Emissions and Removal

Authors: Florence Renou-Wilson, Kenneth A. Byrne, Raymond Flynn, Alina Premrov, Emily Riondato, Matthew Saunders, Killian Walz and David Wilson

Irish bogs have been drastically altered by human activities and the sampled peat properties reflect the nature and magnitude of the impact of land use and management. A recognition of the heterogeneity found across Irish peat soils, together with an understanding of the relationships between key soil properties, are critical for developing effective strategies to reduce the carbon footprint of these degraded ecosystems. Our findings clearly support the need for a site-by-site approach for rewetting management schemes.

Identifying pressures

At EU level, peatlands have been highlighted to play a central role in achieving the temperature goals agreed in the Paris Agreement, and peatlands are already included in the 2030 Climate and Energy Framework [Regulation (EU) 2018/841]. Covering c.20% of the land surface, much of the peatland area has been extensively modified by humans; many peat soils are under a range of land use categories (LUCs), namely grassland, forestry or peat extraction (both industrial and domestic). When the residual peat depths under the LUCs are compared with natural bogs, a picture emerges of more intensive use of raised and mountain bogs than lowland blanket bogs. All land with peat soils is crucial in the global carbon balance, as it contains soils with high carbon content. Whether peatlands continue to store or release carbon is strongly dependent on management and site-specific properties. Action to improve the management of peatlands requires a capability to accurately report greenhouse gas (GHG) emissions/removals.

Informing policy

Peatlands have played an important role in climate regulation over the past 10,000 years. Natural peatlands are a small carbon sink (absorbing carbon dioxide while emitting methane), but 82% of Irish peatlands have been damaged to various extents. Disturbance from human activities, mainly in the form of drainage (for agriculture and forestry) and peat extraction produce increased carbon dioxide and nitrous oxide emissions, and reduced methane emissions. To mitigate emissions from peatlands two actions must be taken: (1) avoid new or recurrent drainage and (2) reduce emissions on the existing drained areas. The rewetted and restored cutover bogs monitored in this study are carbon sinks, while their drained counterparts are substantial carbon sources. Cutover bogs hold large carbon stocks that must be sustainably managed if Ireland wishes to meet its climate change targets.

Developing solutions

Predicting GHG emissions from peatlands requires a fundamental understanding of the role of peatland properties in the carbon cycle. Basic information on the peatland resource and associated properties has permitted a new evaluation of the carbon stock held in Irish bogs and has informed immediate management interventions to prevent further carbon losses from this huge store. Given the heterogeneity of peatlands and the current GHG status across peatland LUCs, more sites must be monitored for GHG dynamics across a wider geographical range.

Although process-based models typically require more site parameter inputs than empirical models, they are more reliable for predicting the variability in GHG dynamics under future environmental and anthropogenic changes. By applying a drainage factor, we successfully improved the water table simulation approach in the ECOSSE model and thus the ability to predict carbon dioxide emissions from drained peat soils; however, further research to improve the water component in the ECOSSE model, together with continuous data collection (particularly water table levels), especially from rewetted sites, are critical to support sustainable peatland management schemes.

EPA Research: McCumiskey House,
Richiew, Clonskeagh, Dublin 14.

Phone: 01 268 0100
Twitter: @EPAResearchNews
Email: research@epa.ie

www.epa.ie

EPA Research Webpages
www.epa.ie/our-services/research/