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Vulnerability Assessment of Peatlands: Exploration of Impacts and Adaptation Options in Relation to Climate Change and Extreme Events (VAPOR)

Authors: Florence Renou-Wilson and David Wilson

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Rialtas na hÉireann
Government of Ireland

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EPA RESEARCH PROGRAMME 2014–2020

Vulnerability Assessment of Peatlands: Exploration of Impacts and Adaptation Options in Relation to Climate Change and Extreme Events (VAPOR)

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by

University College Dublin

Authors:

Florence Renou-Wilson 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

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Cover image: Blanket bog habitat in Glenveagh National Park, Co. Donegal and Tumduff cutaway peatland, Co. Offaly

The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

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

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Executive Summary

The climate changes predicted for Ireland by the end of the 21st century will have significant impacts on drained, rewetted and natural peatland systems. Long-term greenhouse gas (GHG) monitoring studies have shown that Irish peatlands have been impacted by a wide range of environmental conditions over the last two decades. These studies provide robust GHG baseline data that can be used to understand better the effects of climate change on peatland ecosystems. The significance of current land management, as well as mitigation strategies that include rewetting, can be appraised by assessing predicted carbon dioxide (CO_2) and methane (CH_4) exchange, which were modelled at four representative peatland sites.

The results of the climate change simulation scenarios in this study highlight the extreme vulnerability of degraded (drained and rewetted) Irish peatlands to even modest changes in climate (i.e. 1–2°C increase in temperature, reduced summer precipitation). However, CO_2 emissions from rewetted areas were lower than those from their drained counterparts, with some rewetted vegetation communities likely to remain sinks of atmospheric CO_2 even under moderate climate changes. Drained agricultural peat soils are projected to become even larger hotspots of CO_2 emissions with the additional effect of having a large positive feedback on climate change.

Rewetting would appear to offer a buffer to some of the largest increases in CO_2 emissions projected for drained areas at most sites, although, even then, rewetted sites that are currently CO_2 sinks are projected to become CO_2 sources in response to new climate stressors. Future climatic scenarios will also impact CH_4 emissions, albeit with more complex responses. Newly rewetted sites, in a "transition" period, were sensitive to a warmer climate, releasing more CH_4 under warmer conditions. However, this increase was dampened when combined with a lower water table level. The more stable "older" rewetted sites appeared more resilient to increased temperatures.

The results of this study would indicate that rewetting is a climate-proof, effective mitigation strategy, provided that extreme events, such as summer drought, are not recurrent. This is critical, as an increase in both the frequency and the intensity of these extreme events is projected, even with the lower emission "climate change" scenarios. In addition, the longer that a rewetted peatland is established, the more resilient it will be to climate change, so a delay in implementation reduces the probability of successfully re-establishing the carbon sink function and the longer term resilience of the rewetted system (in effect reversing the initial positive effects). Therefore, a swift implementation of rewetting actions to ensure the measure has long-term benefit/sustainability is critical. Finally, our study indicates that current methods of rewetting may need to be reconsidered or supplemented in order to ensure that high water table levels are maintained to promote carbon sequestration.

This study also highlighted that cost-effectiveness analysis (CEA) is a good metric to compare mitigation efforts across climate change policies. The rewetting of industrial cutaway and cutover bogs corresponded to an average cost-effectiveness value of just under €4 per tonne of carbon dioxide equivalent (CO_2-e), which would clearly support such mitigation efforts.

From the observations highlighted by this research, we firstly recommend the establishment of a national management plan to ensure that a sufficient range of natural and rewetted peatlands are properly managed to maintain the water table levels necessary to sustain as many ecosystem services as possible. Additional rewetting projects should be identified as a "low-hanging fruit" mitigation measure.

Secondly, drained peatlands used for agriculture and peat extraction should be targeted for rewetting as a climate mitigation strategy to prevent increased GHG emissions in the future. In particular, the rewetting of industrial cutaway and cutover bogs was shown to be a low-cost intervention supporting an effective mitigation measure.

Thirdly, as keeping the carbon stock in organic soils (by rewetting drained peatlands) can be an effective mitigation measure to reduce CO_2 emissions,

adaptation options may also be required to ensure their “resilience”. This will require continued long-term monitoring of rewetted sites, as well as the promotion of future rewetting projects, to be carried out without further delay and in conjunction with potential sustainable productive systems, such as paludiculture.

1 Introduction

1.1 Climate Change in Ireland

The 21st century is likely to be defined by some of the most extreme and rapid climate changes that the Earth has experienced (IPCC, 2013). Atmospheric concentrations of carbon dioxide (CO_2) and other greenhouse gases (GHGs) have increased significantly above pre-industrial levels and changes have been detected in global surface temperatures and other climatic parameters (IPCC, 2013). Ireland is already experiencing the effects of climate change not only in the average climate, such as air temperature, but also in the pattern and character of extreme weather events (Desmond *et al*., 2017). Ireland has seen an increase in the mean annual air temperature of 0.4°C during the period 1980–2008, a shortening of the frost season and increases in the length of the growing season and the occurrence of species suited to warmer temperatures (http://www.epa.ie). The most recent climate change projections for Ireland indicate that, by 2050, average annual temperatures will rise by between 1°C and 1.6°C, with the greatest change in daily minimum temperatures projected for future winters; the number of frost days will be reduced by 50%, and the length of the growing season will increase by over 35 days per year (Nolan, 2015; O'Sullivan *et al*., 2015). There are also projected to be significant decreases in precipitation in spring and summer (with an increase in the number of extended dry periods, defined as at least five consecutive days with daily precipitation less than 1 mm) but more frequent heavy precipitation events in winter and autumn (Gleeson *et al*., 2013; Nolan, 2015). However, projections around precipitation frequency and distribution remain much more uncertain than those around temperatures (Desmond *et al*., 2017).

1.2 Climate Change Impacts on Peatland Ecosystems

Variations in climate change projections at regional levels are pronounced and these have major implications for our ability as a society to conserve natural ecosystems. Preparing for and coping with the effects of climate – the objectives of climate change adaptation – is now seen as the overarching framework for conservation and natural resource management. In Ireland, coastal habitats, uplands and peatlands are deemed the most vulnerable to climate change and the scale and extent of current species and habitat shifts are anticipated to continue (Coll *et al*., 2012). A modelling study by Jones *et al*. (2006) based on climatic envelopes has suggested that the predicted changes in climate are likely to result in a severe diminution of the Irish peatland cover by 2075. Other Irish studies (Renou-Wilson *et al*., 2011; Coll *et al*., 2014; Coll *et al*., 2016) have revealed that climate change impacts will depend on the type of peatland (lowland peatlands being more affected than upland ones) and especially geographical location (southern regions being more at risk). UK studies have shown that reduced summer rainfall and increased summer evaporation are likely to put stress on peatland plant communities in the late summer and autumn, with conditions becoming too dry (low peat moisture content) in certain parts (Acreman *et al*., 2009), and a long-term decline in the distribution of actively growing blanket peat is forecast (Clark *et al*., 2010), although the authors warn that existing peatlands may well persist for decades under a changing climate. Uncertainties inherent to projections of future regional climate change (especially precipitation) mean that it is difficult to assess the exposure of peatlands to climate change with accuracy.

However, identifying what systems are likely to be most affected (i.e. analysing the exposure of a habitat type to projected changes) is only the first step in trying to understand the complex interactions between climate (regional variations), climate change (unprecedented rates) and individual ecosystems (management and internal biogeochemical feedbacks). Peatlands exist within well-defined climatic thresholds. We know, for example, that blanket bogs require the highest year-round rainfall of all peatlands, combined with low summer temperatures. A study of the fate of blanket bogs around the world using seven different global climate models projected that the bioclimatic space for blanket bog will dramatically shrink and will persist only in limited areas (Gallego-Sala and Prentice, 2012). However, palaeo-environmental reconstructions have revealed that peatlands have responded to past climatic shifts (Lindsay, 2010). For example, peat growth was faster during the Medieval Warm Period than during the later Little Ice Age (Mauquoy *et al*., 2002; Kołaczek *et al*., 2018). To conclude that small increases in temperature may actually increase peat growth rates would be misguided, as this may happen only in cases in which sufficient moisture remains to maintain a high water table level (WTL) or in locations where a short growing season and low temperatures already prevail (Gallego-Sala *et al*., 2016). There is considerable debate as to what the net effects of future climate change and extreme weather events might be on peatlands in general, as there is a lack of studies investigating the biogeochemical processes that occur within various peatland types and in various locations and their inherent negative and positive feedback mechanisms (Charman, 2002; Frolking *et al*., 2011). Firstly, the heterogeneity in biogeochemistry and hydro-ecology that characterises and differentiates peatland systems in different regions inevitably creates variability in their response to changing climatic conditions, with variation even on relatively small scales. Multi-year field studies have been useful in developing parameter coefficients for short-term modelling and in understanding the natural range of variation in the environmental drivers and the response functions of carbon (C) processes to those drivers (e.g. Renou-Wilson *et al*., 2016; Wilson *et al*., 2016a). Long-term GHG monitoring studies demonstrate that bogs can persist as strong CO_2 sinks during drought (Goodrich *et al*., 2017), become CO_2 sources (Lund *et al*., 2012) or sustain a small but resilient CO_2 sink function (McVeigh *et al*., 2014). Secondly, slight changes in climatic variables, such as temperature or precipitation, could affect the potential of a peatland to store C by losing labile soil organic C during dry periods (e.g. Ise *et al*., 2008). This, in turn, would immediately cause a positive feedback effect, i.e. increasing further the amount of CO_2 in the atmosphere and therefore increasing further atmospheric temperatures. Thirdly, the ecological impacts associated with climate change do not exist in isolation, but combine with and exacerbate existing stresses on our natural systems (Glick *et al*., 2011). Positive feedbacks are likely to be associated with projected land use change/management in the response to climate change, i.e. although we know that drained peatlands, for example, are high GHG emitters, their response to climate change in the light of future management (e.g. management of the WTL) prompts large uncertainties (Tiemeyer *et al*., 2016). Therefore, additional pressures in the form of future drainage or other intensive forms of management are a source of concern as to whether or not peatlands can significantly mitigate 21st-century climate change (Frolking *et al*., 2011). Finally, in order to consider the long-term effects of climate change, the complexity of internal synergy and feedback mechanisms inherent in peatland ecosystems needs to be taken into account, especially the response of plants to changing water levels or to elevated temperatures (Jungkunst and Fiedler, 2007; Murphy *et al*., 2009). For example, the response of vegetation could determine whether a peatland becomes more sensitive (Pullens *et al*., 2016) or more resilient (Hedwall *et al*., 2017) to climatic variations.

1.3 What is the Current and Future State of Irish Peatlands?

Irish peatlands provide valuable international and regional ecosystem services (C sequestration and storage, water storage and biodiversity) (Renou-Wilson *et al*., 2011). Inappropriate land use management or failure to act to protect these ecosystems against future climate changes will lead to large-scale degradation, with major environmental and social impacts (Renou-Wilson, 2018). On the other hand, appropriate management decisions can generate multiple benefits including increased resilience to future climate change. Peatlands have played an important role in climate regulation over the past 10,000 years. Natural peatlands (i.e. non-degraded) in Ireland are currently a small C sink (absorbing CO_2, emitting methane (CH_4), exporting dissolved organic C) but these represent less than 20% of the current national resource (Wilson *et al*., 2013a). 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 (which remain high in the ditches). The current state of Irish peatlands and the consequences of widespread degradation in terms of loss of various ecosystem services have been highlighted by previous EPA-funded research (Renou-Wilson *et al*., 2011; Wilson *et al*., 2013b), thereby establishing a framework for the development of a National Peatland Strategy (NPWS, 2014a). As less than 20% of the original area is considered to be worthy of conservation (Douglas *et al.*, 2008), this unique resource will only deteriorate further without intervention, i.e. implementation of the recommendations set out in the National Peatland Strategy for the sustainable management of Irish peatlands. Most of these recommendations, however, have not been fully integrated into a climate change mitigation/adaptation framework. It is highly likely that Irish peatlands will be put under further stress because of climate-mediated disturbances. Both undisturbed and damaged ecosystems will face increases in the severity and frequency of disturbances, as forecast by Nolan (2015), including (1) gradual changes (in temperature; in the amount, intensity and seasonal distribution of precipitation) and (2) extreme events (severe drought; increased wildfires; flooding events). These changes will have significant impacts on the ecosystem functions of the peatland (C store, hydrology and biodiversity) but the severity may vary with the state of the peatlands and existing stressors, placing the future security of these valuable ecosystem services in jeopardy, as well as affecting other downstream natural systems.

1.4 Research Objectives

The VAPOR research project was aimed at assessing the vulnerability of peatlands to climate change and extreme events by improving our understanding of the links between climatic variables, hydrology, ecology and the GHG dynamics of peatlands. Tools were also developed to determine how these important ecosystems are likely to respond to climate change using the latest projections for Ireland.

Understanding vulnerability is central to identifying adaptation needs and contributes to adaptation planning. An assessment of vulnerability can be defined as a “measure of possible harm” (Hinkel, 2011). In this case, harm to a natural resource, such as peatlands, would include, inter alia, a loss of habitat or species diversity, disruption to food webs, reduction in ecosystem services, such as C sequestration and storage, or loss of ecosystem resilience and the capacity to bounce back from stresses, reduced water quantity or quality and an increase in habitat fragmentation. In addition to identifying what function or process will be most vulnerable, such assessment aims to identify actions that will reduce vulnerability by either reducing the impacts of climate change and additional stressors or enhancing adaptive capacity. Overall, this research is critical in developing a deeper understanding among stakeholders of the vulnerability and liability of Irish peatlands with regard to climate change and in providing policy-relevant scientific information in support of an adaptive risk management framework leading to effective mitigation measures and adaptation actions in Ireland (Theme 2 of the EPA strategy 2014–2020; Desmond *et al.*, 2017).

1.5 Methodology

In the first instance, state-of-the-art knowledge is presented on the profile of Irish peatland types (relatively natural bogs, degraded bogs, rehabilitated/restored/rewetted bogs) and their current conditions (providing background on the physical environment, ecological characteristics and social dimension = ecosystem services). Having drawn the background picture, we identify the potential primary and secondary impacts of climate change, including gradual and extreme changes in climatic variables, such as temperature and precipitation as projected (Nolan, 2015), on peatland processes, in particular:

- the hydrology (WTL and hydrochemistry);
- the vegetation (source of positive and negative feedbacks);
- the C balance (both gaseous and fluvial C fluxes affected by vegetation, C dynamics).

The vulnerabilities of peatlands are appraised in combination with current and future stressors associated with land use management.

Secondly, a review of existing datasets from monitored sites provided critical information on the relationships between ecohydrological conditions and climate variables (vis-à-vis long-term averages and extreme events if present), as these ultimately control seasonal and inter-annual variation (IAV) in CH_4 and CO_2 fluxes as well as plant phenology.

Thirdly, we investigated the sensitivity of CO_2 exchange under a range of controlling factors. Within the boundary of existing environmental conditions, we used existing multiple regression models to simulate CO_2 exchange under various WTLs and soil temperatures as a proxy for climatic variables (precipitation and air temperature). We make direct comparison of site sensitivity to climate change under various management approaches and observe whether vegetation composition can modulate annual environmental variability as seen in the datasets. The question "What magnitude of climate change is required to critically affect C dynamics in various peatland types?" is tentatively answered given the existing datasets in Ireland and from investigations abroad.

Fourthly, we investigated appropriate feasible management strategies and their costs and benefits by:

- identifying feasible strategies vis-à-vis current peatland distribution (review of management strategies by land use category and ownership);
- an evaluation of ecosystem services including indirect effects;
- a cost-effectiveness analysis (CEA) of intervention options.

Altogether, the above analysis was integrated into predicted land use changes and climate change scenarios for Ireland in order to inform adaptation strategies for specific sites.

Definitions

In this report, we draw on the Intergovernmental Panel on Climate Change (IPCC) definition of **vulnerability** as the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes (IPCC, 2001). Vulnerability is a function of the character, magnitude and rate of climate change and variation to which a system is exposed (i.e. exposure), its sensitivity to stresses associated with environmental and socio-economic changes and its adaptive capacity or resilience (be it present or absent) (Glick *et al*., 2011). Multiple drivers (stressors) are recognised beyond those related to climate (political, cultural, economic, institutional and technological forces) and also the dynamic nature of exposure, sensitivities and adaptive capacity over time.

$$\text{Vulnerability} = \text{sensitivity} + \text{exposure} + \text{adaptive capacity} \quad (1.1)$$

Exposure: the degree to which a system is exposed to climate factors, including in terms of duration, frequency and magnitude of the changes in average climate and extremes. Exposure of peatlands has been investigated by Coll *et al*. (2014) using bioclimatic envelope models, which show the spatial shift in current species/habitat distribution but give only information about exposure to climate stress, not sensitivity. They lack process information or information on feedbacks once climate has become unsuitable/changed. Process-based simulation models are required to understand the sensitivity and adaptation capacity.

Sensitivity: the degree to which a system is sensitive to change.

Adaptation: action taken to avoid actual or anticipated impacts from climate change or to attain potential benefits arising from climate change (IPCC, 2007).

Adaptive capacity: the preconditions necessary to enable adaptation. The adaptive capacity inherent in a system represents the set of resources available for adaptation, as well as the ability or capacity of that system to use these resources effectively in the pursuit of adaptation. Such resources may be natural, financial, institutional or human and might include access to ecosystems, information, expertise and social networks. Adaptive capacity is expressed as actions that lead to adaptation that serve to enhance a system's coping capacity and increase its ecological resilience.

Ecological resilience approaches view climate change as acting on the dynamic relationships between *and* within human and natural systems (or social–ecological systems). These approaches recognise that social–ecological systems can exist in a range of states, some of which may be more desirable than others. In applying ecological resilience to climate vulnerability, the aim is to identify and avoid thresholds that might move a system to a new, less desirable state or to encourage a system on a trajectory to a more sustainable state.

2 Are Peatlands at Risk from Climatic Changes?

2.1 Profiles of Irish Peatlands at the Beginning of the 21st Century

Peatlands are the main types of wetlands in Ireland and cover between 14% and 20% of the territory (Hammond, 1981; Connolly and Holden, 2009; Xu *et al*., 2018), storing 75% of the national soil C (Renou-Wilson *et al*., 2011). Peat is the remains of plant and animal constituents that accumulated under more or less water-saturated conditions owing to incomplete decomposition (Rydin and Jeglum, 2006). Soil scientists in Ireland define peat as consisting of at least 30% (dry mass) of dead organic material (Renou-Wilson *et al*., 2011). Peatlands are ecosystems with a surface layer of peat of at least 30 cm (on drained land) or 45 cm (on undrained land) but often much thicker (Renou-Wilson *et al*., 2011). Much of this area has been extensively modified by humans over centuries and currently more than 40% of the peatlands do not have the original hydrophytic vegetation, which has been replaced by trees or grass or removed altogether for peat extraction for energy or domestic use (Wilson *et al*., 2013b). Natural peatlands provide important global and regional ecosystem services (C storage, water storage and biodiversity), as well as spiritual, cultural and educational services (Parish *et al*., 2008). The societal benefits of Irish peatlands are based on ecosystem functions that are inherent to peatlands and are tightly interlinked. These functions can be substantially influenced by (1) human activities and (2) climate change and climate extremes, thereby directly influencing the benefits that this natural resource can provide.

The scale and rate of human activities (peat cutting, afforestation and agriculture) affecting peatlands have increased over the course of history and have been supplemented by further land use changes in the form of wind farm developments and recreational activities in the present. These anthropogenic activities generally involve drainage and removal of vegetation, thereby directly impacting on peatland functions through (1) altered hydrology (including water storage capacity and water quality), (2) loss of biodiversity and (3) increased peat oxidation and altered GHG balances. The continued loss of active raised bog habitat within the national protected raised bog network (≈37% between 1994 and 2012) has been directly attributed to turf cutting and associated drainage (NPWS, 2014b).

2.2 Impact of Climate Change and Extreme Weather Events on Peatland Processes

Climate is the most important determinant of the distribution and characteristics of peatlands, affecting location, topography, biodiversity and more importantly biogeochemical cycles. Peatlands have always been part of the global C cycle and climate system acting as dynamic C stores. Key to this role is the position of the WTL within the peat. In undisturbed peatlands, the WTL remains close to the surface and, as a result, rates of decomposition (C loss) are generally lower than rates of productivity (C uptake). In actively removing CO_2 (sequestration) and releasing CH_4 throughout the Holocene they have affected the current global climate, albeit over a long period of time (Frolking and Roulet, 2007). Palaeo-ecological studies of peatlands have shown that peat (and C) accumulation as well as the vegetation composition, and the hydrology of peatlands, have all been altered by past climate change (Charman, 2002; Kołaczek *et al*., 2018). Even during the last millennium, C accumulation rates have responded to changes in cloud cover, temperature and growing season length (Charman *et al*., 2013). Although there has been small negative feedback to changes recorded in the Northern Hemisphere peatlands over the last 1000 years, adequate moisture availability has been critical for C accumulation (Charman *et al*., 2013). Several studies have demonstrated faster rates for peat accumulation in warmer areas, as long as there is sufficient moisture to maintain a high WTL (e.g. Beilman *et al*., 2009; Yu, 2011). Long-term studies have also confirmed the stability and resilience of net ecosystem exchange (NEE) (CO_2 sequestration potential) of certain peatlands, even with moderate inter-annual climatic variations (e.g. Peichl *et al*., 2014). However, anomalous events could also trigger a shift in the peatland C balance at those sites and this apparent resilience may not be sustained under rapid anthropogenic climate changes.

2.2.1 Impact of temperature and moisture changes

Although peatlands are considered generally resilient ecosystems (Robroek *et al*., 2017), for example having the capacity to respond biologically to inter-annual climatic variations (McVeigh *et al*., 2014; Peichl *et al*., 2014; Helfter *et al*., 2015; Levy and Gray, 2015), a significant and more rapid change is expected in GHG dynamics and vegetation composition in the 21st century (Parish *et al*., 2008; Frolking *et al*., 2011). For example, a rapid increase in air temperatures has been shown to lead to increased peat (soil) temperatures (Chivers *et al*., 2009), which in turn leads to increased levels of microbial activity and subsequent peat decay leading to changes in GHG fluxes (Dorrepaal *et al*., 2009; Gong *et al*., 2013).

Although it is assumed that the rate of C flux to the atmosphere (through soil respiration) will increase as soils warm (Bond-Lamberty *et al*., 2004), it is not possible to accurately predict the net response of soil C stores due to ecosystem feedbacks (e.g. increased plant growth) (Smith and Fang, 2010). Higher temperatures and a lengthened growing season may result in improved peatland productivity (Saarnio *et al*., 2003; Peichl *et al*., 2014; Helfter *et al*., 2015) or increased C sequestration in the plant biomass (Strack and Waddington, 2007; Loisel and Yu, 2013) or trigger a negative feedback mechanism from the vegetation (Ward *et al*., 2013), thereby modulating climate change impacts by compensating for the loss of soil C.

The feedback from vegetation is complex and depends on a series of factors, such as nutrient status and plant types. Although increased plant productivity has been reported under higher CO_2 concentrations in nutrient-rich peatlands, with the vegetation composition slightly shifting towards vascular flora and loss of mosses (Freeman *et al*., 2004), other studies did not establish CO_2 fertilisation effects, e.g. in grasslands or forests, and this was attributed to nutrient limitation and the types of plants (e.g. *Sphagnum*) (Berendse *et al*., 2001; Hoosbeek *et al*., 2002).

Although a moderate increase in temperature was found to have negligible effects on plant productivity and community composition in a sedge-dominated boreal fen, modest WTL drawdown drove significant changes and was the more dominant control, leading the authors to conclude that hydrological scenarios are critical in assessing the future of these ecosystems (Mäkiranta *et al*., 2018).

Changes in the frequency and distribution of precipitation (especially during the growing season) will have an immediate impact on WTLs in peatlands and could lead to the cessation of peatland growth (Mitsch *et al*., 2013). This is because *Sphagnum* bogs, for example, can accumulate several metres of peat over millennia (Roulet *et al*., 2007) but require a water level close to the soil surface. A recent Canadian study showed that decreased precipitation frequency will decrease net CO_2 uptake in peatland communities dominated by *Sphagnum*, regardless of other dominant species, e.g. sedges or woody shrubs (Radu and Duval, 2017). Moreover, rainfall frequency during the growing season is a particularly important factor in controlling *Sphagnum* photosynthesis (Robroek *et al*., 2009). Precipitation disturbances, such as lower rainfall, could result in impacts similar to those that occur during drainage and associated WTL drawdown, including changes in species and microhabitat diversity (both cover and number) (Tuittila *et al*., 2004), organic matter decomposition leading to nutrient release and loss of stored C both directly to the atmosphere (as CO_2 and CH_4) (Riutta *et al*., 2007) but also via aquatic systems as dissolved organic carbon (DOC), particulate organic carbon (POC) and evasions of CO_2 from streams (Frolking *et al*., 2010; Renou-Wilson *et al*., 2014; Evans *et al*., 2016).

Conversely, higher precipitation rates could provide a wetter environment, beneficial for the onset of paludification (a peat formation process), even at relatively higher temperatures (Frolking *et al*., 2001), as a raised WTL will decrease CO_2 but increase CH_4 emissions (Petrescu *et al*., 2009; Sonnentag *et al*., 2010), although the magnitude again varies depending on the nutrient status and plant communities (Wilson *et al*., 2016a). In addition, changes in precipitation regimes, such as an increased number of rainy days, is associated with a reduction in light [photosynthetic photon flux density (PPFD)] that may decrease the annual C sink strength of peatlands (Nijp *et al*., 2015).

It is critical here to emphasise the importance of internal feedbacks. In all climatic scenarios, hydrological and plant-related self-regulation can also ensue, impacting on ecosystem processes that themselves can have positive or negative feedbacks on the projected climate change impact. Plants differ in their sensitivity to environmental changes and these may come in many shapes and forms and work in synergy. Feedback mechanisms are typically complex with regard to peatland vegetation, not least for *Sphagnum* mosses. These have a critical response role, as they can maintain a fairly constant water level relative to the surface during high rainfall or mild drought. Such species were present during past climate changes and have been found to be the architects of such resilient habitats (Rydin and Jeglum, 2006).

It has also been shown that extended drier periods may be fatal for *Sphagnum* species (Dieleman *et al*., 2014). Negative feedback loops may also come in the wake of temperature and WTL changes that affect, for example, the canopy cover; an increased canopy cover can better protect mosses from increased heat and direct sunlight (Hedwall *et al*., 2017) or can cause a shift in species composition (Ward *et al*., 2013). These responses may in turn affect the WTLs vis-à-vis the surface of the peatland. It has also been suggested that, following WTL drawdown, the subsidence of the peat surface may shift the system back to the pre-disturbance condition (Dise, 2009).

Research has shown that Irish and New Zealand natural peatlands are resilient in terms of the annual C balance (McVeigh *et al*., 2014; Goodrich *et al*., 2017), whereas other studies in the boreal region have shown increased C accumulation (Loisel and Yu, 2013). Peatlands have also already presented a change in their ecological trajectory (Dise, 2009). Indeed, although physical, hydrological and biogeochemical feedbacks inherent to natural peatlands may buffer some of the perturbations caused by climate change, peatlands can also shift to a new ecosystem with associated large losses of stored C and positive feedbacks, i.e. eliciting further climate change (Ise *et al*., 2008; Dise, 2009; Waddington *et al*., 2014). For instance, the increased cover of *Juncus effusus* at the expense of *Sphagnum* species in a minerotrophic peatland subjected to elevated CO_2 led to increased C turnover and higher DOC concentrations with increased peat decomposition (Fenner *et al*., 2007). In a boreal fen, a drop in WTL affected the relative contribution of different plant functional types in the community, which could lead to critical changes in the functions of fens (Mäkiranta *et al*., 2018). Such feedbacks are complex and trans-disciplinary, making their investigation challenging. Recent meta-analysis of data from 87 northern peatlands demonstrated that the complex interactions between temperature, plant community cover, WTL depth and soil pH are the main determinants of CH_4 emissions (Abdalla *et al*., 2016). There are also uncertainties over the existence of disturbance “thresholds” that affect not only CO_2 and CH_4 feedbacks but also ecosystem structure (Limpens *et al*., 2008). It has been acknowledged that the peatlands most at risk are those that lack the biological capacity to respond to climatic changes because of the absence of “buffer” species such as *Sphagnum* (Gallego-Sala *et al*., 2016). Slight climatic changes may exacerbate the problems for peatlands already in decline and their resilience may be weakened in fragmented ecosystems, such as raised bogs.

2.2.2 Impacts of extreme weather events

Although climate change may be gradual and variable, extreme events may cause abrupt and more persistent hydrological changes. Studies so far have shown that the response of relatively natural peatlands to extreme weather events follows the same short-term impacts of wetting and drying, although studies that have analysed the direct relationships between climate data (precipitation), peatland hydrology and GHG fluxes are still too few (Frolking *et al*., 2011). The impact of droughts or more intense precipitation events is of particular interest, as in both cases additional C is likely to be lost via gaseous and fluvial C exports (Evans *et al*., 1999; Lund *et al*., 2012; Wang *et al*., 2015; Estop-Aragonés *et al*., 2016). However, the timing, severity and duration of drought will control the peatland responses, which are highly variable in space and time (Lund *et al*., 2012; Estop-Aragonés *et al*., 2016). Bog mosses have been found to not be able to recover after a period of drought, thereby affecting the overall ecosystem productivity and the climatic footprint of the bog (Bubier *et al*., 2003; Lafleur *et al*., 2003). *Sphagnum* species are particularly vulnerable to drought because of the lack of control of moisture content in the capitulum during dry conditions (Laitinen *et al*., 2008). However, interestingly for Ireland, perhaps, frequent precipitation patterns could moderate the impact of drought events on the C uptake of certain species of *Sphagnum* (Nijp *et al*., 2014).

Droughts may also affect plant community structure (e.g. with the establishment of competing drought-tolerant shrubs; Churchill *et al*., 2014). Long-term shifts in species diversity present even more complex scenarios that may elicit positive or negative feedbacks on the atmosphere. More drought-tolerant species, such as *Juncus* and *Molinia*, produce more DOC per unit weight (Ritson *et al*., 2017). Vegetation shift is also a controlling factor in predicting CH_4 emissions, more so than warming itself (Ward *et al*., 2013). Other studies have shown that large CH_4 emissions from natural or rewetted peatlands have been recorded during periods of higher rainfall, often coupled with higher temperatures (Olson *et al*., 2013; Günther *et al*., 2014). These impacts can be moderated again by vegetation, e.g. sedge succession may increase CH_4 emissions during wetter periods but attenuate further emissions in drier periods (Strack *et al*., 2006). At our study site, Blackwater, County Offaly, a 12- to 16-year-old rewetted industrial peatland, CH_4 emissions from sedge microsites were low and comparable to those from natural peatland ecosystems, compared with higher emissions from areas colonised with *Phragmites* (Renou-Wilson *et al*., 2018a).

In the context of extreme weather events, the occurrence of wildfire is another hazard, which in combination with increased vulnerability of peatlands caused by climate change will bring higher risk to these ecosystems (Flannigan *et al*., 2009; IPCC, 2010) with direct negative impacts in the form of biodiversity and C loss (Robinson, 2009). Fires can affect natural and, more likely, managed peatlands (peat extraction and forestry). This is because management practices in drained and mined peatlands have destabilised a range of ecohydrological feedbacks, as well as vegetation and soil properties that would otherwise moderate water and C losses in natural peatlands. Following observations of the current high burn severity of drained tropical/temperate peatland fires, it has been suggested that large-scale drained and mined northern peatlands are now also more vulnerable to wildfire under climate change (Granath *et al*., 2016). Wildfire C losses reported in Canada and Russia have not only caused a positive feedback loop but also are a major environmental problem contributing to the decline of biodiversity and ecosystem functions as well as smoke pollution causing health problems. To prevent deep peat burn, it is critical to rewet the mined peatlands ensuring high peat moisture content and a layer of hydrophilic vegetation (ideally mosses) (Granath *et al*., 2016). Post-fire emissions, especially CH_4, are also complex and may vary depending on the type of char (burnt vegetation) and nutrient content of the peat (Medvedeff *et al*., 2015). Furthermore, post-fire recovery of keystone species, such as *Sphagnum* mosses, may also be jeopardised by erratic hydrological settings (Lukenbach *et al*., 2015), leaving *Sphagnum*-dominated peatlands even more vulnerable to low WTL positions post fire (Kettridge *et al*., 2014).

Finally, at the biophysical level, extreme weather events in the form of higher rainfall intensity would lead to increased erosion and loss of particulate C. Northern hemisphere blanket bogs located at low latitudes (e.g. Ireland) have been found to be at most risk of fluvial erosion under 21st-century climate change (Li *et al.*, 2017). This may jeopardise the peat mass, leading to potential peat slides or bog bursts with further indirect negative impacts on water quality downstream and associated risks to both aquatic biodiversity and infrastructure/humans (Lindsay and Bragg, 2004; Boylan *et al*., 2008). The issue of erosion and mass stability of peat is more acute for blanket bogs and especially those already under pressure (degradation from overgrazing or wind farm development) (Boylan and Long, 2010). Overall, a complex web of primary and secondary impacts together with positive and negative feedbacks, acting alone and in synergy, can be identified (Figure 2.1).

2.3 Impacts of Climate Changes on Managed Peatlands and Synergies with Land Use Change

Anticipating the response of peatlands to climate changes in the medium to long term is a considerable challenge that is exacerbated by the coupling with other stressors such as land use changes and management. Studies point to the fact that degraded peatlands are likely to be more vulnerable to climatic variations than undisturbed peatlands, worsening climate change by losing C through (1) gaseous emissions (CO_2, but also CH_4 in ditches) and (2) aquatic pathways (DOC and POC) as well as (3) wind erosion and fires (Lindsay, 2010; Wilson *et al*., 2015). In addition, management decisions such as inappropriate grazing and burning regimes or

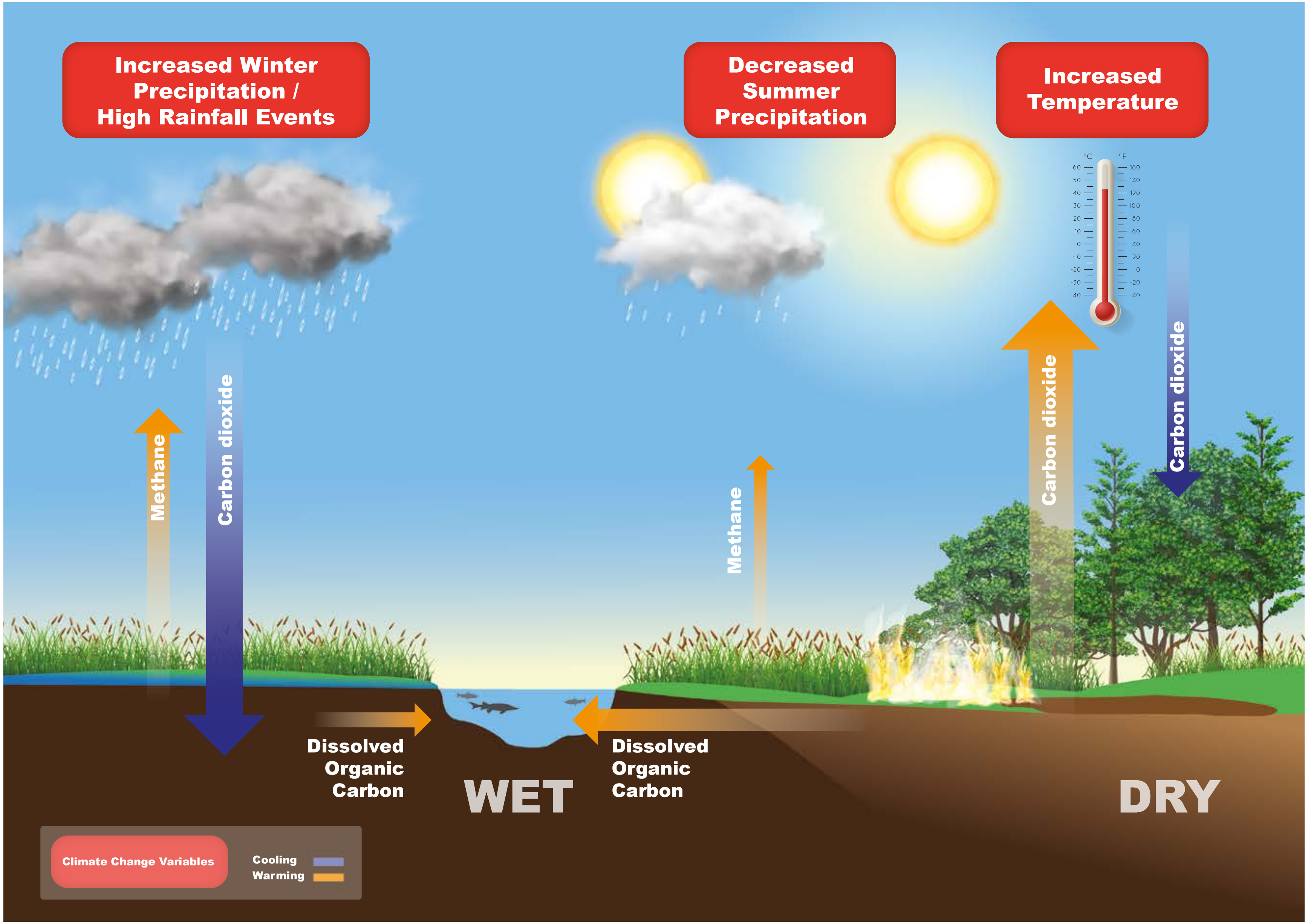

Figure 2.1. Infographic representing the effects of climate change on peatland biogeochemical processes.

turf cutting will provoke further adverse effects. The increased risk of fires is of high concern in terms of both preventing large losses of C stock and human health, as seen with the burning of Indonesian and Russian peatlands (Gaveau *et al.*, 2014). The assessment of the severity of these adverse effects is complicated by the type of existing land use and management, which may also be more susceptible to climate change. Peatlands that have "developed" through past droughts or flooding over the two millennia have shown more severe susceptibility to a dry climate in the last century as a result of drainage and peat extraction (Kołaczek *et al.*, 2018). During drought periods, managed peatlands (forestry, crops or grassland) may become deeply drained, impairing primary productivity (Reichstein *et al.*, 2013) as well as oxidising more peat (Tiemeyer *et al.*, 2016). However, this relationship is very dynamic and lower emissions have actually been recorded during very dry periods (Tiemeyer *et al.*, 2016), as soil respiration is limited by both very high and very low soil moisture contents (Glatzel *et al.*, 2006; Toberman *et al.*, 2008). On the other hand, the reduced productivity (as a result of lower rainfall, for example) may affect these utilised peatlands, with the risk of future abandonment and continued release of CO_2 as well as fluvial emissions (Maljanen *et al.*, 2013; Pellegrino *et al.*, 2015).

The implications of extreme weather events for managed peatlands are likely to be even more complex because of these additional stressors. The predicted impacts are likely to be more severe (Gallego-Sala *et al.*, 2016) for associated habitats. For example, weather conditions, in particular extreme rainfall events following prolonged drought periods, can significantly increase phosphorus concentrations and sediment loading in streams following clearfelling on afforested upland blanket peat catchments (Rodgers *et al.*, 2010), to the detriment of salmonids and freshwater pearl mussels located within peat catchments (O'Driscoll *et al.*, 2011).

The level of degradation of the peatland ecosystem should be recognised as one of the main controlling factors with regard to the severity of the impact. Suitable management strategies could make them more resilient to changes, as seen in natural peatlands. For example, it would appear that both severely damaged bogs (industrial cutaway peatlands) and low-level degraded bogs (drained only but not cut or planted) require attention here, as both could be rewetted to help stabilise the delivery of ecosystem services and more critically to mitigate climate change (Renou-Wilson *et al.*, 2018a).

Rewetting of drained organic soils has been initiated at several sites across the country with the aim of (1) reducing net GHG emissions at the source and/or (2) creating suitable conditions for C sequestration in active peatland habitats. However, concern over "climate-proofing" peatland rewetting and restoration efforts is a serious issue that has not been addressed, e.g. it is absent in current restoration funding mechanisms (e.g. EU LIFE projects). Will money spent restoring vast areas of peatlands be worth the investment if future climate change creates unfavourable conditions for peat formation? On-going work at a partially restored bog (Ballynafagh, Co. Kildare) suggests that, in winter, water levels are very close to the ground surface in most vegetation assemblages, but that greater variations occur in summer (R. Flynn, Queen's University Belfast, 2017, personal communication). The first implication is that, in the context of predicted increased rainfall and intensity in the winter, a lack of additional water storage capacity in a raised bog will lead to excessive runoff. The second implication is that any reduction in the water supply during the growing season will greatly impact on the vegetation (i.e. *Sphagnum* moss).

A preliminary estimate suggests that up to 100 Pg of CO_2 equivalent (CO_2-e) could be released to the atmosphere from wetlands and peatlands over the next 100 years (Gruber *et al.*, 2004). Wetlands International has estimated the total annual C loss from degraded peatlands at 1.3 Gt C yr^{-1} (Joosten, 2009), compared with the estimated C sink from northern peatlands of 0.076 Gt C yr^{-1} (Gorham, 1991). In Ireland, the figures are even more striking, with degraded peatlands, together with the burning of the peat, estimated to release 3 Mt C yr^{-1}, whereas, in comparison, natural Irish peatlands are estimated to sequester 0.072 Mt C yr^{-1} (Wilson *et al.*, 2013b). Notwithstanding the high uncertainty associated with all these estimates, it can be concluded that, in a future warmer climate, peatlands would be likely to cause a positive feedback to the climate system, with the caveat that negative feedbacks may occur in certain sites. An overview of the main effects of climate change scenarios on peatland functions is summarised in Appendix 2.

3 Retrospective Analysis of Monitored Peatlands

In this chapter, we examine existing datasets from monitored peatlands providing information on recently recorded climate variables (vis-à-vis long-term averages and looking at extreme events if present) and hydrological conditions and their role in the seasonal and IAV in C balances (CH_4 and CO_2 and fluvial C fluxes if measured), as well as plant phenology. Further information and locations of the peatland sites can be found in Appendix 1.

3.1 Meteorological Data

A short study of Met Éireann climatic data indicates that climatic conditions needed to support active bog habitats did not deteriorate between 1990 and 2010, as annual precipitation and rainfall intensity/ number of rain days did not significantly change over the country during this period (NPWS, 2014b). However, this analysis based on 12 weather stations (with only three located west of the Shannon) did not assess the impact of increased temperatures, leading to increased evaporation and lowered water tables. Changes in temperatures (both averages and extreme) have been observed in Irish records in recent decades and are expected to continue in the future. An analysis of datasets from various peatland locations across Ireland demonstrates that a wide range of environmental conditions affected Irish bogs over the last two decades.

At **Glencar** blanket bog (Co. Kerry), the monitoring period spanning 2002–2012 included some of the warmest months and wettest months and years, as well as some of the coldest winters, in Met Éireann's national archives (McVeigh *et al*., 2014). Seasonal and annual precipitation variance was very high, reflected in the high variation in WTL: the wettest year was 2009, leading to the highest annual mean WTL (–2.6 cm), whereas the lowest WTL (–7.0 cm) was recorded the following year in 2010, the driest year for the study period. The difference in annual rainfall between these two years was a substantial 748 mm. County Kerry has a typical oceanic climate with low summer temperatures and mild winter temperatures propitious to blanket bog formation. However, half-hour average air temperatures recorded over 10 years at Glencar ranged from 27.9°C in summer 2006 to –11.1°C in December 2010 (McVeigh *et al*., 2014). The 30-year annual temperature averages from Valentia Met Station, County Kerry, increased from 10.4°C (1961–1990) to 10.9°C (1981–2010) (https://www.met.ie/climate/available-data/historical-data). It was also recorded that the start of the growing season at Glencar blanket bog varied by as much as 1 month (McVeigh *et al*., 2014).

At **Bellacorick** industrial cutaway bog (Co. Mayo), warmer and wetter conditions were also recorded during the 5-year monitoring period (2009–2013) (Wilson *et al*., 2016b). Two years (2009 and 2011) were 7% and 11% wetter than the long-term average, whereas the other 3 years were 10–15% drier. As with Glencar, 2010 was also the coldest year with the lowest air temperature (Belmullet Station) of –7.6°C, corresponding to a lowest on-site measured soil temperature of –0.4°C. The highest air temperature was 27.8°C, corresponding to an on-site measured soil temperature of 19.6°C, recorded in the summers of 2012 and 2013. The 30-year annual temperature averages from Belmullet Station increased from 9.6°C (1961–1990) to 10.3°C (1981–2010) with the absolute maximum reaching 30°C for the first time in historical records (https://www.met.ie/climate/available-data/historical-data).

This wetter and warmer pattern was also recorded at the **Glenvar** peaty grassland site (Co. Donegal), which was monitored for 4 years (2011–2015) (Renou-Wilson *et al*., 2016). Although annual precipitation was between 10% and 30% higher than the 30-year long-term average, the additional rainfall mostly fell during the winter months (Renou-Wilson *et al*., 2016). Meanwhile, higher temperatures were recorded in the summer months, with the widest annual temperature range recorded during the 4-year period oscillating between –3.6°C and 23.4°C. The 30-year annual temperature averages from Malin Head Station also increased from 9.3°C (1961–1990) to 9.8°C (1981–2010) (https://www.met.ie/climate/available-data/historical-data). Of note, the increased rainfall recorded during the two first summers, coupled with higher temperatures, did not translate into higher productivity. Instead, it was demonstrated that plant productivity was negatively affected by the lack of sunshine during those “dim” periods.

Blackwater (industrial cutaway bog in Co. Offaly) and **Moyarwood** (cutover bog in Co. Galway) are only 30 km apart, located east and west of the Shannon River, respectively. Both sites displayed high IAV and departure from long-term averages in all climatic variables recorded during the monitored period (2011–2015) (Renou-Wilson *et al.*, 2018b). The long-term annual temperature averages from Claremorris Station increased from 8.9°C (1961–1990) to 9.3°C (1971–2000) (https://www.met.ie/climate/available-data/historical-data). Data from local Met Éireann stations (Gurteen Station for Blackwater and Athenry Station for Moyarwood) show that the 30-year mean annual air temperature (1980–2010) was slightly lower at Blackwater (9.6°C), which was strongly affected by lower winter temperatures in the area, than at Moyarwood (9.9°C). Very wet and very dry years were both recorded during the GHG monitoring period. Higher rainfall than the long-term averages has also been reported, with on average 245 mm more precipitation in Moyarwood than in Blackwater during the monitoring period. Despite the proximity between sites, extreme weather events were more often recorded in Blackwater, with a significantly dry period recorded in May 2013 and April 2014, coupled with high temperatures that negatively affected vegetation growth, particularly the reed communities (*Phragmites australis*) in Blackwater (Renou-Wilson *et al.*, 2018a).

3.2 Hydrological Data

Peatlands are essentially a hydrological entity and can be considered to be wetlands that accumulate peat when the water table remains close to the surface for much of the year and when the normal amplitude of water table fluctuation is relatively small. Water is the single most important factor enabling peat accumulation and water-logged conditions are a prerequisite environmental parameter for peat formation and preservation. Changes in the hydrological regime that sustains the peatland will invariably disturb the normal hydro-ecological functioning of the peatland. Therefore, hydrological conditions are extremely important for the maintenance of the peatland’s structure and function.

The water balance of an area dictates the form, or type, of peatland that develops. As peat is decaying organic matter that has accumulated under saturated conditions, its formation occurs in areas of positive water balance (Holden *et al.*, 2004) where the volume of water entering the system (e.g. precipitation, surface runoff, groundwater upwelling) is greater than that leaving the system (e.g. runoff, seepage to groundwater, interception and evaporation). Not all those components of the water balance operate in all peatlands.

As seen in all monitored peatland sites, WTL fluctuations can occur over relatively short time frames and their amplitude will depend on (1) inputs (effective rainfall), (2) the position relative to a discharge (i.e. drains or outlet) and (3) storage properties of peat. At all monitored sites, it was observed that WTLs follow similar seasonal and annual patterns to those of precipitation (e.g. Figure 3.1).

However, IAVs in WTL were also observed at all monitored sites. Table 3.1 summarises the values for the deepest and highest annual mean WTL recorded at each site during the monitoring period. The hydraulic conductivity (K) of the peat most notably determines the level of the water table (zone below which water pressure is greater than atmospheric pressure) whereas the capacity of the peat to store water influences how much the WTL will fluctuate. These parameters can vary by many orders of magnitude from one peatland to the next and from one area of the bog to the next. They are, however, necessary, along with the precipitation and evaporation data, in order to model the WTL. Although work is currently being carried out to develop such a model at the rewetted raised bog site in Moyarwood, we still lack an empirical model to predict the WTL and therefore its variation under climate change. From long-term observations, however, we can infer that, although natural sites show relatively small WTL fluctuations, drained peatlands are more at risk from changes in rainfall patterns, leading to an increased rate of fluctuations, which will lead to faster decomposition. This may be partially explained by the fact that soil temperature is more readily affected by air temperature when the WTL is deeper in the soil, as drier soils heat (and cool) faster than wetter soils, which can remain stable for longer (Collins and Cummins, 1996). For rewetted sites, changes in the rainfall pattern could more critically affect the amplitude of the WTL fluctuations and therefore jeopardise the "climate-proofing" of such management intervention.

3.3 Carbon Balances and Variations in CO_2 and CH_4 Balances

3.3.1 General overview from the last 15 years of field data collection across Ireland

Before expanding on how future climate change is likely to alter the functions and processes of peatlands, we should dwell on how peatlands are currently affecting and being affected by climate controls, recognising the high uncertainty associated with both the role of peatlands in the C cycle and the role of climate change in future peatland ecosystems. Field-based studies covering the range of peatland types (nutrient poor or rich), status (drained to rewetted to near-natural) and land use categories (forestry, grassland and peat extraction) have produced precise individual-site knowledge of the climatic footprint of Irish peatlands. The main observations are summarised below:

- Natural peatlands currently act as small C sinks (Laine *et al*., 2007a; Sottocornola and Kiely, 2010; Koehler *et al*., 2011; McVeigh *et al*., 2014).
- Drained peat soils are significant hotspots of CO_2 emissions and are strongly controlled by soil temperature, WTL and vegetation composition (Wilson *et al*., 2015, 2016b; Renou-Wilson *et al*., 2016, 2018b).
- Rewetting can provide GHG benefits for climate regulation by either decreasing high CO_2 emissions or, for the better sites, returning the C sink function characteristic of natural bogs. However, this capacity clearly depends on site characteristics and not only on previous land use management (Renou-Wilson *et al*., 2016, 2018a,b; Wilson *et al*., 2016b).
- Rewetting increases CH_4 production in the enhanced anaerobic zone. As the solubility of CH_4 in water is a function of the water pressure, which is dictated by the WTL, CH_4 reaches higher concentrations when water levels are high. On the other hand, when the WTL drops for a short period, the water becomes supersaturated and exsolution (formation of gaseous CH_4) below the water table will occur. On the next phase of raising of the WTL, higher rates of CH_4 are likely to be emitted (Hahn *et al*., 2015). The fact that rewetted sites may be more prone to future drying or flooding (because of unstable management of the WTL) is likely to make them prone to additional CO_2 emissions (oxidation of CH_4 during low WTLs) and CH_4 emissions (during very high WTLs) (Mahmood and Strack, 2011; Vanselow-Algan *et al*., 2015).

There is still considerable uncertainty over predicting the C balance of all peatland sites, even in the same region as those studied here, because of the existing unique vegetation pattern and history of each site. Long-term monitoring of ecosystems requires time-consuming and expensive monitoring programmes but allows the possibility to analyse multi-year datasets and establish robust long-term estimates of C balances as well as understand the complex relationships between abiotic variables (temperature, radiation, WTL, etc.) and gaseous and fluvial C fluxes. These can in turn be used to monitor the effects of climate change (Wu *et al*., 2013; Wu and Roulet, 2014). Ireland had five such long-term monitored sites: a near-natural Atlantic blanket bog (Glencar, 10 years); a rewetted industrial blanket bog (Bellacorick, 5 years and, to our knowledge, the longest GHG study at a rewetted peatland); two rewetted industrial raised bogs (Blackwater and Moyarwood, both 4 years); and a rewetted peaty grassland (Glencar, 4 years). All rewetted sites included simultaneous monitoring of a drained part of the site. Together, these sites have provided critical information on what drivers affect GHG exchange and whether changes in climatic variables (via IAV) could critically affect the C balance.

3.3.2 Site-specific GHG budgets across Ireland

Near-natural site: Glencar

With 10 full years of CO_2 measurements, the near-natural blanket bog site at Glencar, County Kerry, is the longest continuous peatland CO_2 monitoring site in Ireland and among nine other such sites in the world. It has been supplemented at various times with studies that have sampled CH_4, and by fluvial studies that have quantified the export of DOC. The observed variation in climatic variables during the 10-year monitoring period confirmed that, although the CO_2 sink was reduced during dry years, Glencar remained

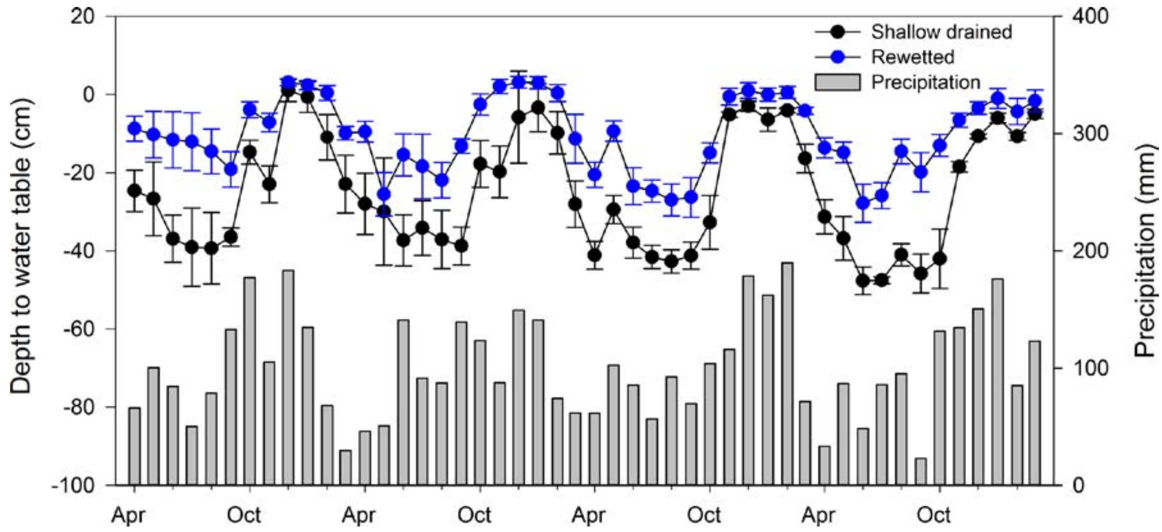

Figure 3.1. Water table levels (cm) and precipitation (mm) at the drained and rewetted peaty grassland (Glenvar, Co. Donegal) over the 4-year monitoring period. Negative values indicate a WTL below the soil surface.

Table 3.1. Lowest and highest annual WTL means recorded during the GHG monitoring periods at various natural and managed peatlands (drained and rewetted), together with monthly minima and maxima

Site	Status	Monitoring years	Deepest annual mean WTL (cm)	Highest annual mean WTL (cm)	Min. deepest monthly WTL (cm)	Max. highest monthly WTL (cm)
Glencar	Near-natural	10	–7	–2.6	–13	0
Bellacorick	Drained	2	–30	–22	–70	–13
Bellacorick	Rewetted – bare peat	5	–3.9	–0.1	–40	+5
Bellacorick	Rewetted –vegetated	5	+3.5	+15.5	–29	–21
Blackwater	Drained	4	–57	–22	–80	–22
Blackwater	Rewetted	4	–10	+1.3	–43	+19
Glenvar	Drained	4	–28.9	–22.8	–57	+4
Glenvar	Rewetted	4	–13.9	–7.3	–44	+5
Moyarwood	Drained	4	–49	–52	–68	–40
Moyarwood	Rewetted	4	–2	+1.5	–20	+11

a resilient ecosystem with NEE being influenced mostly by the WTL (McVeigh *et al.*, 2014).

Rewetted industrial cutaway (nutrient-poor) blanket bog: Bellacorick

To the best of our knowledge, the rewetted site at Bellacorick, County Mayo, is the longest-running GHG study at a rewetted peatland (Wilson *et al.*, 2013a, 2016b). The 5-year monitoring study (2009–2013) demonstrated that CO_2 exchange (NEE) varied between years and was largely determined by respiration (autotrophic and heterotrophic), which was in turn driven by soil temperatures and the WTL. The rewetted site was a very strong CO_2 sink in 4 out of the 5 years due to lower-than-average rainfall and elevated soil temperatures in early 2010. Annual CH_4 emissions were also driven by soil temperature and the WTL and varied considerably within the site (i.e. between vegetation communities). The IAV in CH_4 emissions was not as strong as for NEE (Wilson *et al.*, 2016b), although annual emissions were higher than for comparable natural sites (cf. Laine *et al.*, 2007b; Levy and Gray, 2015).

Rewetted industrial cutaway raised bog: Blackwater

Greenhouse gas monitoring took place over a 4-year period (2011–2015) at the rewetted (nutrient-rich) industrial cutaway at Blackwater, County Offaly. In the years since the drainage pumps were de-activated, the site has become a mosaic of open water, vegetation (mainly reeds and sedges) and (drained) bare peat areas. There was considerable IAV at all microsites, with the reeds (*P. australis*) and the sedges acting as a net annual CO_2 sink in the first 2 years and a net annual CO^2 source in the following 2 years. However, the large CO_2 sink afforded by the reeds meant that this microsite remained an overall sink, unlike the sedges community. As at Bellacorick, the annual CO_2 balance was largely determined by respiration (autotrophic and heterotrophic), driven by soil temperatures and WTL, although IAV in gross primary production (GPP) was also evident in both communities (Renou-Wilson *et al*., 2018a). Methane emissions in both vegetation communities were surprisingly low when compared with more intact fen ecosystems (cf. Nykänen *et al*., 1995; Drewer *et al*., 2010; Günther *et al*., 2014). However, although accounting for 30% of the rewetted site, GHG dynamics in the open water were not quantified during the study and research from other flooded peatland sites or peatland lakes suggests that it might be a significant GHG hotspot (Repo *et al*., 2007; Franz *et al*., 2016).

Rewetted drained-only raised bog: Moyarwood

The site was rewetted in 2012/13 and GHG monitoring began immediately afterwards in the newly rewetted area. The rewetted area has been a CO_2 sink in the 4 years of GHG monitoring thus far, with NEE steadily increasing with each successive year. With the exception of a short period in 2013, the WTL has remained stable and close to/above the soil surface. As a result, respiration rates over this time have been very low, whereas GPP rates have increased as plant species more characteristic of intact sites (e.g. *Sphagnum*) have recolonised and spread. In contrast, CH_4 emissions across the 4 years have been relatively high, particularly for a nutrient-poor site. This is probably caused by high methanogenic activity in response to elevated levels of organic matter inputs, from root exudates and litter but also from the "old" vegetation cover now submerged under the high WTL (Hahn-Schöfl *et al*., 2011).

Rewetted peaty grassland (sloping): Glenvar

The annual weather pattern was relatively stable during the 4-year monitoring period at Glencar, with one interesting deviation from the long-term average in the form of colder and wetter periods (Renou-Wilson *et al*., 2016). Cold and wet weather during the growing season impacted CO_2 fluxes primarily by decreasing soil respiration as a result of cooler soil temperatures but this was counteracted by a decreasing productivity (low biomass production) because of lower radiation ("dimmer" conditions). Increased precipitation in the wintertime (a predicted climate change scenario for this region; McGrath and Lynch, 2008) did not influence seasonal or annual CO_2 fluxes. In other sites further north, colder winters or late snow have been shown to decrease summer NEE sinks (Herbst *et al*., 2013; Helfter *et al*., 2015). During the cold, non-growing period, the WTL was habitually close to the surface and, because of the gentle slope, flooding did not occur; therefore, winter GHG fluxes remained unaffected, unlike in the intact Atlantic blanket bog at Glencar (Laine *et al*., 2009). However, over the 4-year study, the WTL was found to be a dominant driver of long-term variability in CO_2 fluxes, as found in other studies (Helfter *et al*., 2015). Therefore, controlling and managing the WTL during the growing season especially will be critical to maintain the climatic footprint of these sites (Renou-Wilson *et al*., 2016).

Drained peat soils (2 years in Bellacorick, 4 years in Blackwater, Moyarwood and Glenvar)

All the drained peat soils were annual sources of CO_2 with the highest emissions observed in Blackwater followed by Bellacorick, Moyarwood and Glenvar (in descending order). With the exception of Moyarwood, no CH_4 emissions were observed at any of the drained sites.

3.4 Overview of 15 Years of Monitored Sites with Regard to Management Options

The long-term monitoring of five peatland sites has been critical in understanding the impact of management options (natural and drainage vs rewetting of peat soils) on GHG dynamics. Rewetting represents a significant saving in terms of avoided CO_2 emissions in comparison with drained peat soils. Drained cutover and cutaway bogs represent substantial hotspots of GHG emissions that will continue and are most likely to increase the release of CO_2 into the atmosphere as the WTL drops lower and soil temperatures increase further. The frequency of drought events will also determine the potential of a rewetted site to mitigate GHG emissions. Although rewetted sites still fluctuate between GHG source and sink over short time scales, the data demonstrated that, while the sites can be hydrologically restored, there is a potential for improvement in terms of management actions, e.g. promoting colonisation of certain species to increase C sequestration or resilience to future drought-like conditions.

4 Climate Change Scenarios and Modelling Analysis of Predicted CO_2 and CH_4 Exchange

4.1 Modelling Premises and Scenarios

In order to investigate the sensitivity of the main climate functions of peatlands (CO_2 and CH_4 exchange), we used long-term study sites (4/5 years) under variable management approaches across a range of peatland types and land uses: grassland (Glenvar), industrial cutaway (Bellacorick and Blackwater) and cutover bog (Moyarwood). These long-term environmental and GHG flux (chamber) datasets in both drained and rewetted areas have provided information on the impact of annual weather variability on NEE. Statistical response functions estimated for gross primary production (GPP) and ecosystem respiration (R_{eco}) were used to reconstruct annual CO_2 balances using site-specific models driven by soil temperature, solar radiation, soil WTLs and leaf area index. The modification of some of the model parameters to fit predicted future climate scenarios for the region allowed potential changes in modelled NEE to be assessed. Response models using environmental controls such as soil temperature and WTL were also developed to estimate annual CH_4 emissions.

Given the long-term study period and statistical range of environmental variables, the GHG flux monitoring datasets and associated statistical and physiological response models parameterised for each study site were found to be robust for such sensitivity simulation (Riutta *et al*., 2007; Laine *et al*., 2009). A database of models detailing the response of GPP and R_{eco} at each site, under a range of controlling factors, was created (see Appendix 2 and associated publications). The models that included soil temperature and WTL were used to simulate CO_2 exchange (GPP and R_{eco}) under multiple scenarios using the following three trends:

1. annual increases in soil temperature: +1 and +2°C;
2. seasonal (summer or winter) variation in WTL: wetter = 5 cm shallower; drier = 10 cm deeper;
3. combination of both soil temperature and WTL alterations.

In addition, the scenarios included a frequency of occurrence over the period of monitoring years (*n*). When the controlling factors were changed for 1 year only (1/*n*), the average of each possible permutation of year was taken. The list of scenarios used for this study is presented in Table 4.1. Summer months comprised the period from 1 June to 1 September and winter months covered the period from 1 December to 1 March.

This method was replicated for CH_4 fluxes when datasets allowed the creation of a statistical model controlled by soil temperature and/or WTL (rewetted Bellacorick, Moyarwood and Blackwater sites only). CH_4 emissions have been found to be negligible at most drained sites (see Renou-Wilson *et al*., 2016,

Table 4.1. List of scenarios simulated for each modelled GHG flux at the various long-term monitoring sites (*n* = number of monitoring years)

	Scenario	Description
A	Wetter winters	Mean winter WTL was 5 cm shallower each year
B	Drier summer (1/*n*)	Mean summer WTL was 10 cm deeper for 1 summer
C	Drier summers (*n*/*n*)	Mean summer WTL was 10 cm deeper each year
D	1°C warmer (1/*n*)	Mean soil temp. was 1°C higher for 1 year
E	1°C warmer (*n*/*n*)	Mean soil temp. was 1°C higher each year
F	1°C warmer drier summers (*n*/*n*)	Mean summer WTL was 10 cm deeper and mean soil temp. was 1°C higher each year
G	2°C warmer drier summers (*n*/*n*)	Mean summer WTL was 10 cm deeper and mean soil temp. was 2°C higher each year
H	2°C warmer (1/*n*)	Mean soil temp. was 2°C higher for 1 year
I	2°C warmer (*n*/*n*)	Mean soil temp. was 2°C higher each year

2018a; Wilson *et al.*, 2016b). The models were used to simulate possible CH_4 exchange under the above scenarios and included plots located in the drains. Results are first analysed and presented here by site, depending on management (drained vs rewetted), and when possible by vegetation communities (rewetted only). Both CO_2 (NEE) and CH_4 were presented using the same units of g C m^{-2} yr^{-1}.

4.2 Modelling Simulation Results

4.2.1 CO_2 exchange

Glenvar: drained and rewetted grassland

The main scenario combinations of interest and predicted NEE for the drained and rewetted grassland sites at Glenvar, County Donegal, are presented in Figure 4.1 against the estimated 4-year mean (2012–2015). In the drained site, CO_2 emissions increased with both increased soil temperature and lower WTL, both individually and in combination. However, warmer scenarios (D–G) resulted in higher increases in emissions compared with drier summers (Figure 4.1). On the basis of this analysis, a persistently warmer climate would more than double CO_2 emissions from this nutrient-poor drained site to values similar to those for nutrient-rich drained sites that are currently recognised as CO_2 hotspots (Renou-Wilson *et al.*, 2014).

When drier summers or warmer years are infrequent (Scenarios B–D) the rewetted site loses its CO_2 sequestering capacity but still remains almost neutral. However, it becomes a CO_2 source when the WTL is lowered and the increase in annual soil temperature becomes frequent (Scenarios E–G).

Although infrequent wetter winters did not impact NEE at either site, regular wetter winters (Scenario A) led to a slight decrease in CO_2 emissions compared with

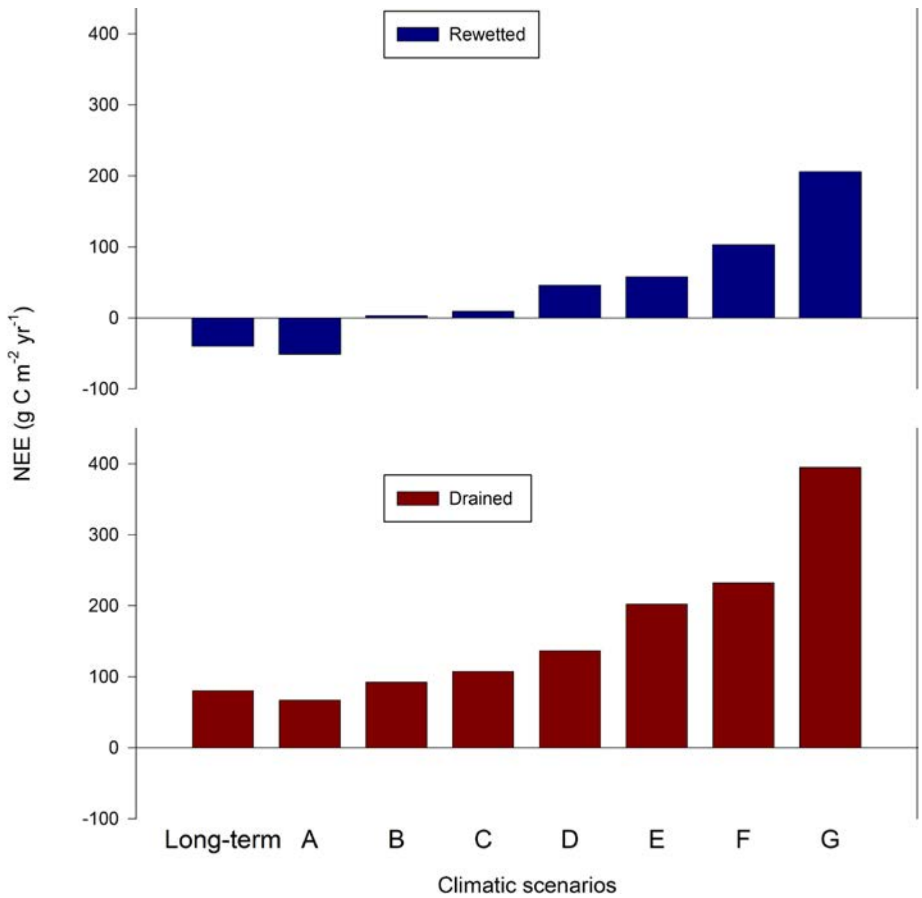

Figure 4.1. Predicted NEE (g C m^{-2} yr^{-1}) at the drained and rewetted grassland sites at Glenvar, Co. Donegal, for a range of climate change scenarios (see Table 4.1 for description) compared with the long-term (4-year) mean. Positive NEE values indicate a loss of CO_2 from the peatland to the atmosphere and negative NEE values indicate CO_2 uptake by the peatland.

the long-term mean in the drained sites (15%) and increased the CO_2 sink potential of the rewetted site by 27%.

These simulations demonstrate that the rewetted Glenvar site is highly sensitive to changes in WTL, whereas soil temperature is the main driver at the drained site. The worse-case scenario (G) combining frequent 2°C warmer and drier summers resulted in an almost fivefold increase in CO_2 emissions in the drained sites in relation to the long-term mean, whereas CO_2 emissions from the rewetted site were approximately half of the drained site emission values.

Bellacorick: drained and rewetted industrial cutaway (nutrient poor)

The drained area of Bellacorick is mainly non-vegetated (bare peat) and shallow drained (see Table 3.1) and therefore only R_{eco} was simulated in this analysis. This drained site was more sensitive to the drier scenarios (less rainfall) than to the increased temperature scenarios, resulting in a 5% (Scenario B) to 11% (Scenario C) increase in CO_2 emissions (Figure 4.2). In the drained area, the warmer and drier combinations led to an increase in CO_2 emissions of 15% and 19% (in comparison with the 5-year mean) for the 1°C and 2°C warmer scenarios (F and G), respectively.

In the rewetted area, the vegetation communities were modelled separately to account for their different response to the climatic controls, such as WTL and soil temperature. The rewetted *Sphagnum/Eriophorum* microsites were only slightly affected by the infrequent dry summer (Scenario B), but a systematic drop in WTL of 10 cm (Scenario C) resulted in all microsites becoming a CO_2 source, albeit the *Juncus/Sphagnum* communities were a smaller CO_2 source than the drained site under current conditions (138 g C m^{-2} yr^{-1}).

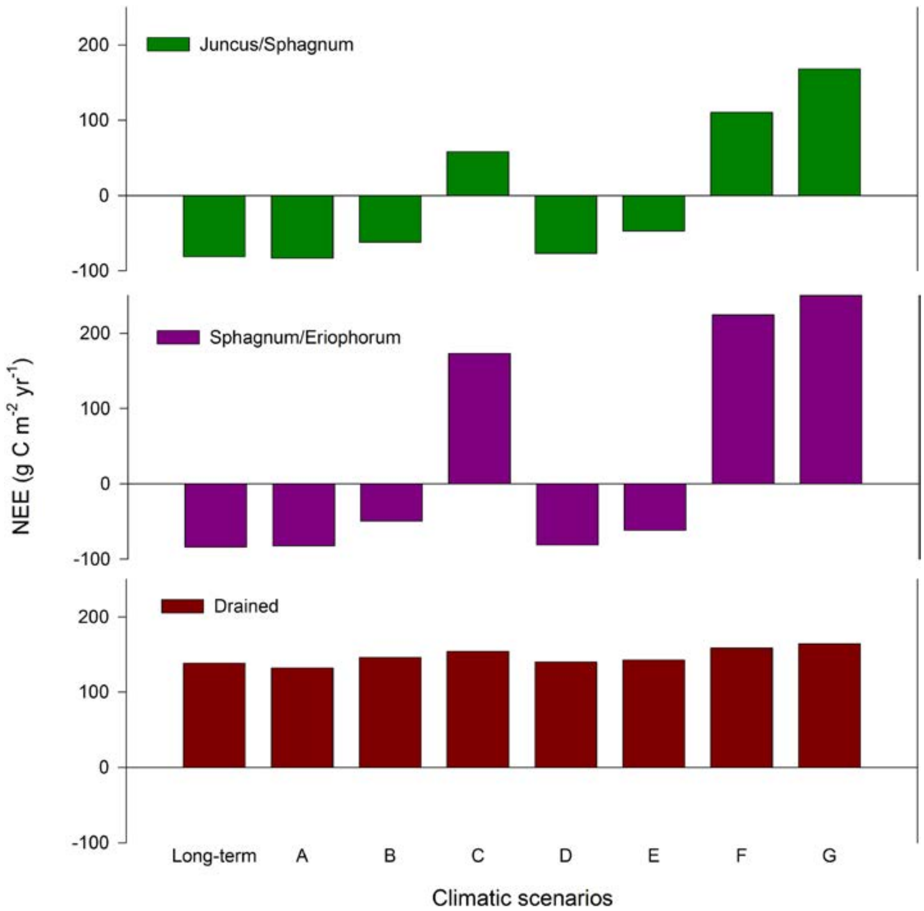

Figure 4.2. Predicted NEE (g C m^{-2} yr^{-1}) for the drained area and for two rewetted vegetation communities at Bellacorick, Co. Mayo, for a range of climate change scenarios (see Table 4.1 for description) compared with the long-term (5-year) mean. Positive NEE values indicate a loss of CO_2 from the peatland to the atmosphere and negative NEE values indicate CO_2 uptake by the peatland.

All microsites were resilient to the 1°C warmer scenarios (D and E). However, the combination of drier summers and warmer conditions turned all microsites into large sources of CO_2. Although the models indicate that GPP was quite sensitive to changes in WTL and R_{eco} was influenced by both WTL and soil temperature, the decrease in wetness may be more critical for rewetted vegetated communities. However, under such environmental conditions a change in vegetation would be likely to occur, with more productive (woody) species developing on the site.

Overall, the rewetted site at Bellacorick is likely to be highly sensitive to a future drying climate and, therefore, preventing WTL drawdown is important to ensure that these vegetation communities remain at least neutral in terms of CO_2 emissions. Given that the drained area is also shallow drained, ensuring a high WTL would also prevent emissions and reduce the risk of future wildfires in these areas.

Moyarwood: drained and rewetted cutover

The drained plots at Moyarwood displayed long-term CO_2 emissions comparable to the drained area at Bellacorick. However, the WTL remained consistently very deep (≈50 cm) and this environmental variable was not included in the statistical response models, as it was found to have no effect on CO_2 fluxes. However, a warmer climate increased CO_2 emissions by between 16% and 33% for the 1°C warmer scenarios (D and E) and between 33% and 70% for the 2°C warmer scenarios (H and I), depending on how frequently the scenario recurred (Figure 4.3).

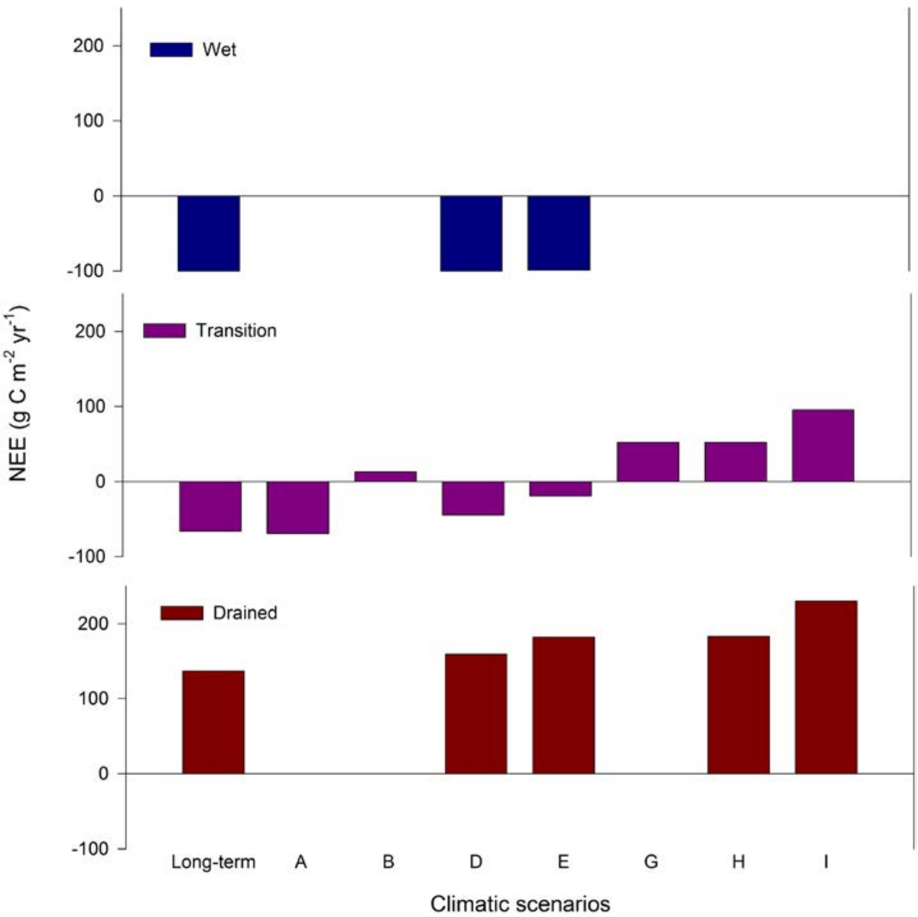

Figure 4.3. Predicted NEE (g C m^{-2} yr^{-1}) at the drained and rewetted sites in Moyarwood, Co. Galway, depending on time since rewetting (2 years following rewetting = "transition"; 3+ years after rewetting = "wet") for a range of climate change scenarios compared with the long-term (2-year) mean. Positive NEE values indicate a loss of CO_2 from the peatland to the atmosphere and negative NEE values indicate CO_2 uptake by the peatland.

The WTL in the rewetted area in Moyarwood was constantly close to the surface or above, especially after the initial 2 years after rewetting (Table 3.1). In this initial period, Moyarwood corresponds to an ecosystem in "transition" and this is reflected in the presence of both WTL and soil temperature in the response models for R_{eco} generated for this period (Renou-Wilson *et al*., 2018a). Years 3 and 4 after rewetting, on the other hand, reflect a more stable "wet" ecosystem in which the vegetation has re-established and is thriving under the very wet conditions. Therefore, models to estimate R_{eco}, for example, were developed for this more stable period without WTL as an explanatory variable (i.e. there was little or no variation in WTL throughout the year). Scenarios decreasing the WTL were therefore not run for this ecosystem. On the other hand, soil temperature was included in both the R_{eco} and the GPP models. Thus, it was possible to assess whether changes in GPP or in R_{eco} were more important with regard to NEE under the climatic scenarios.

These simulation results demonstrated that bogs "in transition" following rewetting may be very sensitive to a drop in WTL. The "transition" site became a source of CO_2 only when drier summers occurred frequently. On the other hand, the "wet" site was resilient to warmer temperatures, showing that climatic variables increased GPP more than they increased R_{eco}, and in terms of CO_2 emissions the site remained similar to the long-term mean.

Blackwater: drained and rewetted industrial cutaway peatlands (nutrient rich)

The drained area at Blackwater was bare of vegetation and recorded the deepest mean annual WTL (–57 cm) of all the monitored drained sites, although even deeper monthly values were recorded (Table 3.1). CO_2 emissions were relatively constant over the 4-year monitoring period, averaging 151 g C m^{-2} yr^{-1}. They did not significantly increase for the scenarios based on infrequent recurrence (Scenarios B and D) but increased with systematic warmer climates (Scenarios C, F and G), with the increase ranging from 10% to 31% depending on the scenario (Figure 4.4). Given the existing environmental conditions at the drained site, the peat is currently oxidising over a deep profile and therefore predictions of WTL change, or even changes in soil surface temperature are not likely to result in more oxidation than already exists.

The rewetted area of Blackwater is dominated by two vegetation communities: (1) reeds (*P. australis*) and (2) sedges (*Carex rostrata, Eriophorum angustifolium*). The reeds remained a CO_2 sink or nearly neutral for most of the scenarios based on infrequent recurrence (Scenarios B and D). Sedge CO_2 emissions were increased by between 7% and 30% in the infrequent scenarios (Scenarios B and D). However, both communities became large sources in the frequent warmer and drier climate scenarios (Scenarios C, F and G). A recurrent drier summer with an annual increase of 2°C would see emissions from the rewetted plots of the same magnitude as those for the drained area (Figure 4.4). Of note, the reeds show less sensitivity to a recurrent drop in WTL and remain a CO_2 sink when wetter winters and drier summers are predicted (with no change in soil temperature).

4.2.2 CH_4 exchange at rewetted sites

Moyarwood: rewetted cutover

Statistical models built to estimate CH_4 emissions from the rewetted site in Moyarwood included both WTL and soil temperature for the 2-year "transition" period and only soil temperature for the following years. CH_4 emissions were higher in the 2-year "transition" period, especially in comparison with natural sites, and this period also appears to be more sensitive to climatic variables, with an increase in CH_4 emissions as a result of increased temperatures (Figure 4.5; Scenarios D and E). However, this increase is dampened when a decreased WTL is added (Scenarios F and G). The "wet" site meanwhile appears more resilient to increased temperatures (Scenarios D and E). However, concurrent vegetation change is not integrated in our scenarios. Ward *et al*. (2013) investigated similar peatland sites in northern England, currently with comparable CH_4 emissions, and found that, under warming conditions (+1°C), a vegetation shift will affect CH_4 emissions more than environmental variables induced by warming.

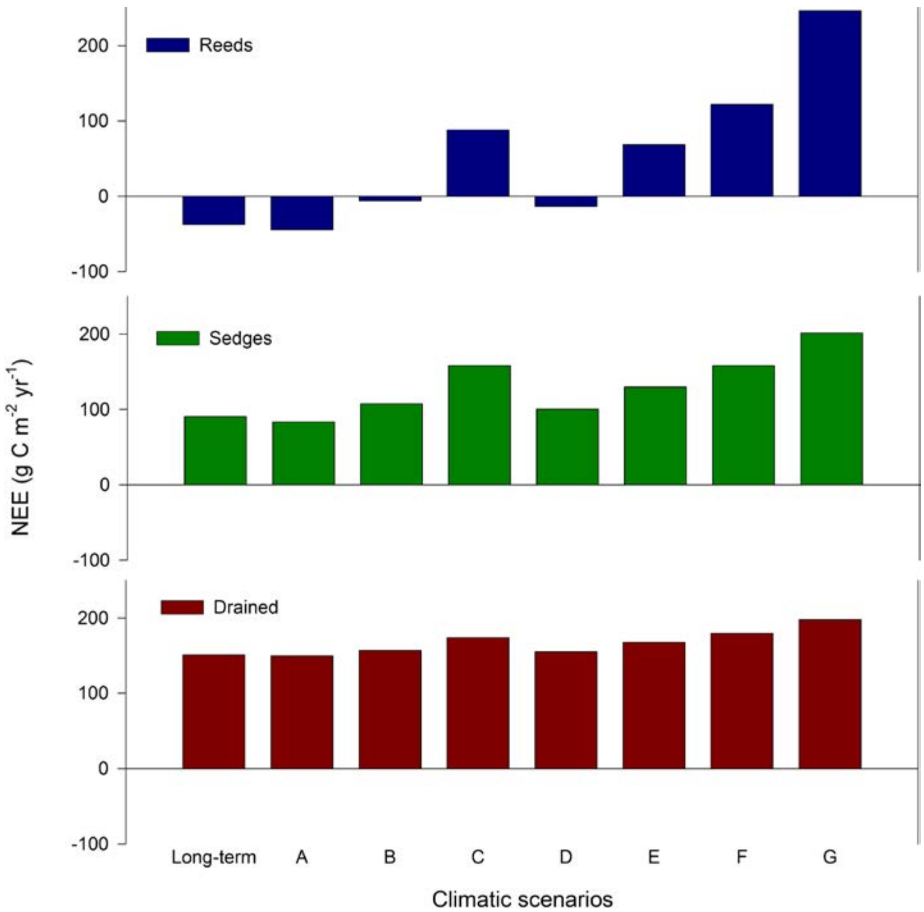

Figure 4.4. Predicted NEE (g C m^{-2} yr^{-1}) at the drained and rewetted sites in Blackwater, Co. Offaly, for a range of climate change scenarios (see Table 4.1) compared with the long-term (4 year) mean. Positive NEE values indicate a loss of CO_2 from the peatland to the atmosphere and negative NEE values indicate CO_2 uptake by the peatland.

Bellacorick: rewetted industrial cutaway

Three vegetation communities were monitored at the rewetted Bellacorick sites: (1) *Eriophorum*, (2) *Sphagnum/Eriophorum* and (3) *Juncus/Sphagnum*. The model to estimate CH_4 emissions included both WTL and soil temperature for both (2) and (3), whereas WTL was absent for (1). Simulations over the 4-year period demonstrated that the lowest annual CH_4 emissions would be produced during years with recurrent drier summers (Figure 4.6; Scenario C), although this decrease would be dampened if combined with wetter winters. The largest increase occurs with warmer temperatures when the WTL remains stable (Scenarios D and E). However, without engineered intervention to keep the WTL high, drier summers will most likely lead to a drop in WTL and therefore CH_4 emissions would remain at their current level. It is worth noting that the frequency of climatic scenarios during the CH_4 simulations in both Bellacorick and Moyarwood is of relative insignificance except in the scenario of recurrent 2°C warmer years. In addition, the models used for *Eriophorum* did not include WTL and appear to be resilient to warmer climates.

Blackwater: rewetted industrial cutaway

The model to estimate CH_4 emissions included only soil temperature and the simulations demonstrated that the reed community, which emitted the highest CH_4 emissions over the 4-year period, was more sensitive to an increase in soil temperature than the sedge community, with CH_4 emissions increasing by 47% for the worse-case scenario (Figure 4.7; Scenarios D and I). Sedges were not affected by changes in soil temperature.

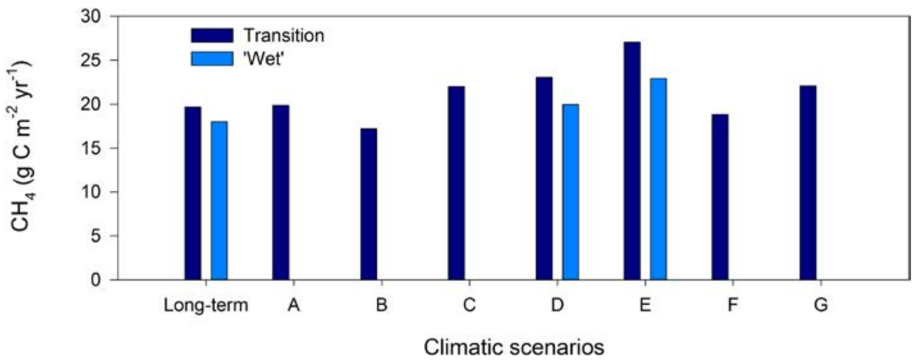

Figure 4.5. Predicted CH_4 (g C m^{-2} yr^{-1}) emissions from the rewetted site in Moyarwood depending on time since rewetting (2 years following rewetting = "transition"; 3+ years after rewetting = "wet") for a range of climate change scenarios (see Table 4.1) compared with the long-term (2-year) mean. Positive values (*y*-axis) indicate a loss of CH_4 from the peatland to the atmosphere.

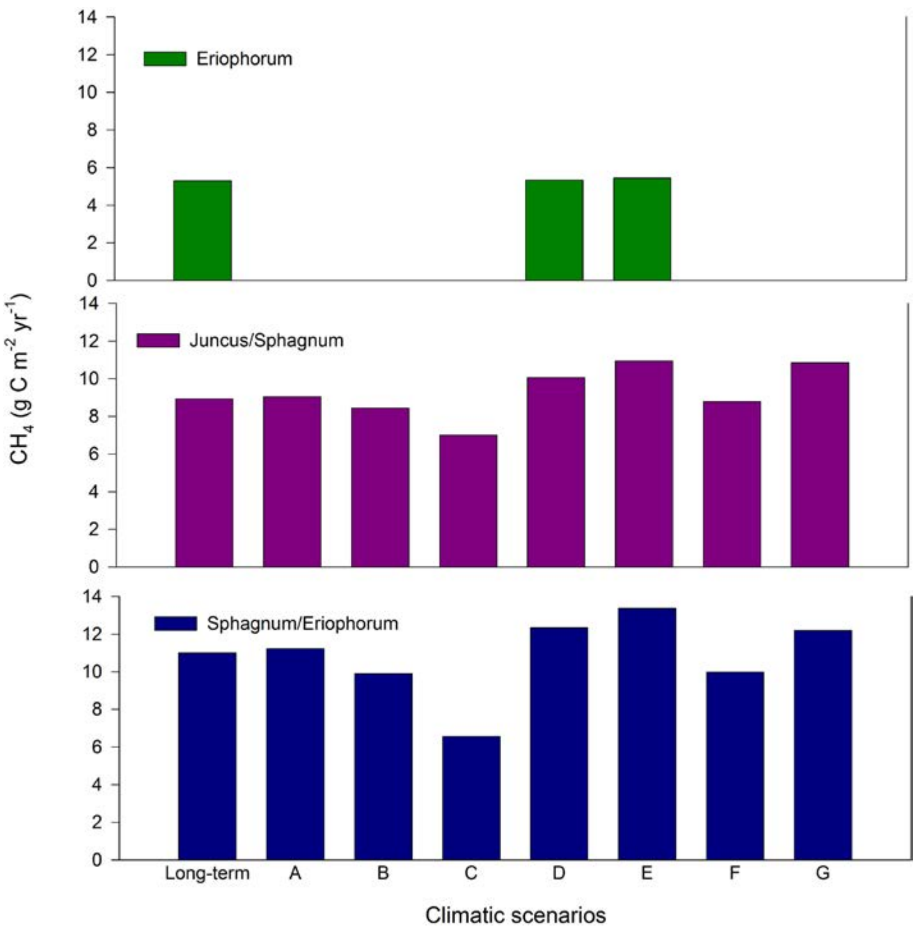

Figure 4.6. Predicted CH_4 (g C m^{-2} yr^{-1}) emissions from the rewetted site in Bellacorick according to the vegetation communities *Eriophorum*, *Juncus/Sphagnum* and *Sphagnum/Eriophorum* for a range of climate change scenarios (see Table 4.1) compared with the long-term (4-year) mean. Positive values (*y*-axis) indicate a loss of CH_4 from the peatland to the atmosphere.

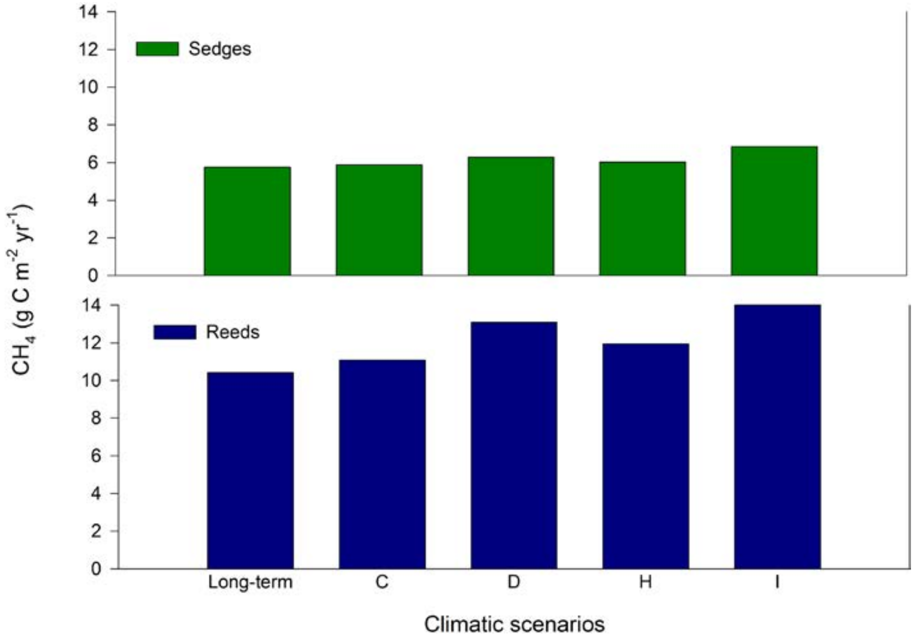

Figure 4.7. Predicted CH_4 (g C m^{-2} yr^{-1}) emissions from the rewetted site at the drained and rewetted sites in Blackwater, Co. Offaly, for a range of climate change scenarios (see Table 4.1) compared with the long-term (4-year) mean. Positive values (*y*-axis) indicate a loss of CH_4 from the peatland to the atmosphere.

4.3 Overall Findings from Simulations

- Infrequent wetter winters do not appear to be significant for either CO_2 or CH_4 exchange.
- Deep drained sites (such as Moyarwood) were very sensitive to soil temperature changes, whereas shallow drained sites were sensitive to the WTL. Therefore, preventing a drop of WTL in shallow drained sites would ensure that these sites remain minimally impacted in terms of CO_2 emissions.
- Rewetted sites were mostly sensitive to the WTL and turned into annual CO_2 sources if a drought-induced drop of –10 cm in WTL occurred in successive summers.
- Under simulated moderate scenarios of (1) increased soil temperature (1°C) and (2) deeper WTL (–10 cm), the rewetted grassland and reed-colonised cutaway sites displayed a larger change (increase) in annual NEE. The least degraded cutover site that was rewetted at Moyarwood, on the other hand, was very resilient to warmer temperatures because of the simultaneous impact on both productivity and respiration (because of the presence of *Sphagnum* mosses). However, no consensus exists as to whether these changes in both productivity and respiration will remain coupled through time (Wu and Roulet, 2014). Moreover, both CO_2 and CH_4 exchange, especially in peatlands, are variable in space and time.
- Except for the “wet” site at Moyarwood (least disturbed before rewetting), all rewetted sites became CO_2 sources when drought and a warmer climate became the norm. Although positive feedbacks from vegetation may occur following such environmental changes, it is expected that the rewetted peatland areas will remain at risk under even moderate levels of climate change and may require further intervention.
- As demonstrated in other studies (e.g. Lafleur, 2009), droughts are likely to be the strongest climatic control on CO_2 fluxes, exacerbating CO_2 emissions from drained bogs, and will strongly influence whether rewetted/natural peatland sites remain a net sink of CO_2 or become a net source.
- The picture for CH_4 is less clear, reflecting the complexity of the quantifying environmental controls for this flux. Although it may not be a critically impacted gas in the short term, the range of rewetted peatland types may also display a wider range of responses.

5 Cost-effectiveness Analysis and Feasibility Strategies

5.1 Cost-effectiveness Analysis of Intervention Options

5.1.1 Premise and choice of methods

Climate mitigation measures should be introduced as soon as possible, as the longer mitigation is delayed, the more costly this will be for society in the long term, although the worst expected impacts of climate change are thought to be avoidable if strong mitigation and adaption processes are put into place soon (OEH, 2013; IPCC, 2014a). It has been estimated that action to combat climate change to a sufficient level could cost 1% of global gross domestic product (GDP) annually at present, whereas inaction will lead to costs of between 5% and 20% of GDP annually in the future (Stern, 2007). In order to encourage the adoption and implementation of beneficial policy, it should be shown to be cost-effective and therefore mitigation strategies should show value for money. The valuation of ecosystem services fails to take into consideration the characteristics of each site, especially its historical land use.

In this study, CEA was selected over other methods of assessment, as it allows consideration of a non-monetary objective (Cellini and Kee, 2010). The mitigation aim is to reduce GHG emissions, which is hard to quantify in monetary terms, so CEAs provide a cost-per-unit benefit (UNFCCC, 2011; Watkiss, 2013). It is now the most commonly used technique to assess climate change mitigation plans, is relatively simple to conduct and tends to be familiar to policymakers (Watkiss, 2013).

Although the benefits of rewetting peatlands across Ireland have been assessed from a climatic and biodiversity perspective, these have not been presented in non-economic terms (Renou-Wilson *et al.*, 2018b). For example, Renou-Wilson *et al.* (2018b) highlighted the climate benefits from rewetting certain degraded peatlands in terms of reduced GHG emissions and the return of the C sink function characteristic of natural (non-degraded) peatlands in many cases, as well as increased biodiversity provision. The benefits were particularly evident for drained-only and domestic cutover areas (e.g. Moyarwood). But rewetted industrial cutaway peatlands, such as Bellacorick, also demonstrated increased provision of other ecosystem services, such as recreation and ecotourism, for example. It becomes apparent that not all benefits can be considered economically. This is a drawback of CEA whereby a single metric must be chosen in order to compare interventions and therefore other benefits are not considered (Watkiss, 2013; Berry *et al.*, 2015). CEA does not consider if the project is necessary and it does not consider the feasibility or equity issues (Chisin, 2009). Further problems include use of a discount rate. This is important in climate change mitigation, as the benefits are likely to be realised much longer after the costs are incurred and so discounting is necessary to compare costs at different points in time (IPCC, 1996; Cellini and Kee, 2010). Deciding on the appropriate discount rate to use involves a value judgement, which is influenced by market preferences, and there is little consensus on how this should be done (Cellini and Kee, 2010). Uncertainty over climate change is an additional problem, as different projections of future climate change will result in different outcomes in climate-related projects; CEA tends to ignore this and could be improved by considering different cost estimates for different emission scenarios. The time frame considered in this study is 50 years, as chosen for other climate change-related peatland studies (Joosten *et al.*, 2015). We applied this time frame to specific sites where the rewetting date is known (e.g. in the case of Bellacorick this is the period 2002–2052, dating from the year when large-scale rehabilitation began; Wilson *et al.*, 2013) or used it as a hypothesis for sites yet to be rewetted. This time frame should cover most of the costs and benefits of the programme; however, if an area remains in a rewetted state, the programme could provide benefits for a much longer period into the future.

5.2 Case Studies: CEA of Rewetting Peatlands

5.2.1 *Methodology*

The aim was to quantify and determine the cost per unit effectiveness, i.e. the cost (€) per tonne of CO_2-e not emitted as a result of the rewetted scheme. Cost-effectiveness can be estimated using the following equation:

$$CE = \frac{Total\ Cost}{Total\ Effectiveness} \quad (5.1)$$

where *total effectiveness* is the amount of CO_2-e removed from the atmosphere over 50 years as a result of the intervention and *total cost* corresponds to the amount of expenditure over the 50 years discounted at the present value.

Cost estimation

The first part of this analysis is concerned with rewetting solely and with the further productive use of the site. The purpose of rewetting is to raise the WTL and therefore expenditure is realised mostly in the initial years when such intervention is carried out. Maintenance and other activities, such as irrigation, may also be required. Firstly, data were acquired for existing rewetting projects of various sizes carried out by Bord na Móna: Bellacorick (≈4500 ha), Moyarwood (≈200 ha) and Blackwater (≈10 ha). The initial costs were incurred during the first and second year and typically included the cost of machinery work for building the bunds or dams; although there is an economy of scale, the average cost was estimated at €400 ha^{-1} (Table 5.1). Future costs include monitoring of the bog and removal of encroaching trees as well as other maintenance costs; an average per hectare has been calculated based on current visits at those sites (Catherine Farrell, Bord na Móna, 2016, personal communication). Spillover costs (costs outside the geographical area under investigation) are unlikely to be relevant, as the surrounding land in all cases is mostly owned by Bord na Móna. Opportunity costs should also be considered. These are other uses the land could be put to and which generate an income. Bord na Móna has stated that industrial cutaway peatlands are to be dedicated to biodiversity and wind energy uses (Bord na Móna, 2016), which would imply no demand for these locations for infrastructure or agriculture. Wind energy production has begun on some sites (e.g. Bellacorick) without hindering the rehabilitation work or vice versa. Therefore, no additional opportunity costs were deemed necessary for these sites.

Table 5.1. Costs (€) of rehabilitating or rewetting Bord na Móna bogs

Intervention	Cost per ha (€)
Rewetting site preparation: dams/bunds	400 (one-off)
Monitoring and tree removal	10 (per year)

Present value cost

In order to accurately report expenditure over long periods, the cost of future spending must be discounted so that all future costs are equated with those of the present (Cellini and Kee, 2010). This is known as the present value cost (PVC) and is used to ensure that future spending is accounted for at the same value as present spending. PVC is determined by the equation:

$$PVC = C1 + \frac{C2}{(1+r)^1} + \frac{C3}{(1+r)^2} + \frac{C4}{(1+r)^3} + \ldots \quad (5.2)$$

where *C* is the cost of each individual year and *r* is the discount rate. A discount rate of 3% was selected, as this is thought to be a representative rate used in economics (Roberts, 2012). Environmental economists often suggest rates around 6% whereas the Stern review suggests a very low 0.1% for long-term climate change issues (Stern, 2007; Aldred, 2009).

The PVC incurred for rewetting Bord na Móna bogs is thus estimated at €655 ha^{-1} over the 50-year period.

CO_2-e emissions/removals

Total effectiveness is the total amount of GHGs in CO_2-e that have been reduced and/or sequestered as a result of the intervention and therefore requires knowledge of the long-term emissions/removals of CO_2 and CH_4 fluxes before and after rewetting. The drained sites were used as a proxy for the "before" intervention and included both CO_2 from the land and CH_4 emissions from ditches (CH_4 emissions from drained sites are negligible). We used our long-term GHG monitoring sites where both drained and rewetted datasets were available. This permitted the effectiveness of the rewetting intervention on one of the common land uses in Ireland, namely peat extraction (both industrial and domestic), to be determined.

To back up this analysis, we also used Tier 1 emission factors (EFs) for peatlands in the temperate climatic zone, published in the IPCC Wetlands Supplement (IPCC, 2014a), for each land use category (peat extraction, grassland) and for the appropriate management (drained/rewetted/ditches) as well as nutrient (rich/poor) category. Aquatic C losses (e.g. DOC) were not included in this analysis. Emissions were all converted into CO_2-e (CO_2-e ha^{-1} yr^{-1}). CH_4 emissions were converted to CO_2-e according to their global warming potential (GWP) on a 100-year timescale: CH_4 = 28 (Myhre *et al.*, 2013).

5.2.2 CEA of rewetting Bord na Móna cutaway and cutover bogs

Bellacorick

Since peat extraction ended at Bellacorick, a rehabilitation project has begun at this large-scale industrial cutaway involving blockage of drains and creation of peat ridges leading to a higher WTL, development of areas of open water and revegetation (Wilson *et al.*, 2013b). The bog was left to regenerate with only monitoring and tree removal occurring after the initial process of rewetting. The entire 6500 ha of the Oweninny complex where Bellacorick is located has not been included in the rewetting scheme. The areas included are those that had drain blockage carried out, namely areas of cutaway (1250 ha), shallow production (1000 ha), deep production (1000 ha) and new development (1274 ha), totalling 4524 ha or 70% of the total site (Fallon *et al.*, 2012).

The site-specific datasets of GHG fluxes measured at Bellacorick showed that drained bare peat emits on average 5.06 t CO_2-e ha^{-1} (Wilson *et al.*, 2016b). However, in the "no intervention" scenario, this bare peat has become fully colonised with *J. effusus* over a 10-year period and therefore drained emissions for the next 40 years are estimated from this vegetation community, which sustained a reasonable WTL of –26 cm on average and emitted 1.54 t CO_2-e ha^{-1} (Wilson *et al.*, 2016b). Over the 50-year period, this drained site would have emitted 112 t CO_2-e ha^{-1}, in addition to 38 t CO_2-e ha^{-1} from the CH_4 emitted from the ditches (total of 150 t CO_{2}-e ha^{-1}).

Bellacorick was rewetted in 2002 and data for post-rewetted emissions/removals were determined by simulating the percentage change in bare peat, vegetation cover and open water using data on ground cover over the 10-year period since rewetting from Fallon (2013) and using the 5-year mean NEE values (monitored between 2009 and 2013) for the dominant rewetted vegetation communities (Wilson *et al.*, 2016b). This rewetted mosaic was a sink of –3.81 t CO_2-e ha^{-1} and was used for the first 20 years post-intervention period together with the measured CH_4 emissions (3.36 t CO_2-e ha^{-1}). For the remaining 30 years, the mosaic of vegetation is considered to resemble that of a natural blanket bog. Therefore, an average from two natural bogs was taken to simulate expected emissions from Bellacorick in this period. These were Glencar, County Kerry (McVeigh *et al.*, 2014), and Forsinard in Scotland (Levy and Gray, 2015), both of which are blanket bogs with similar climatic conditions to those at Bellacorick. The averaged EF was a sink of –3.09 t CO_2-e ha^{-1}. For comparison, the Tier 1 EF from the Wetlands Supplement (IPCC, 2014a) was a more conservative –0.84 t CO_2-e ha^{-1} for nutrient-poor (temperate) peatlands. Conversely, the Tier 1 EF for drained peatlands managed for extraction is higher than the site-specific EF. Over the 50-year period, the rewetting intervention would reduce emissions by 151 t CO_2-e ha^{-1}, as the drained peatland area would emit approximately 150 t CO_2-e ha^{-1} whereas the rewetted site would remove –0.9 t CO_2-e ha^{-1}. Using Tier 1 EF values, the reduction would be higher at 422 t CO_2-e ha^{-1}. The cost-effectiveness values range between €4 and €2 per tonne of CO_2-e avoided for the site-specific and Tier 1 estimates, respectively (Table 5.2).

Blackwater

At Blackwater, drainage pumps were switched off, which, together with blocking of some drains, led to a rise in the WTL in the industrial cutaway peatlands. Over the 50-year period, the drained site is estimated to emit 315 t CO_2-e ha^{-1}, whereas the rewetted site is a lower source of emissions at 215 t CO_2-e ha^{-1}. The rewetting intervention at Blackwater would achieve a reduction of 100 t CO_2-e ha^{-1}. This compares with

Table 5.2. Summary comparison of the cost-effectiveness in euros (€) per tonne of CO_2-e avoided of rewetting various Bord na Móna peatlands for a 50-year period

Site name	Data source	50-year avoided emissions (CO_2-e ha^{-1})	CE (€ per t CO_2-e)
Bellacorick (lowland industrial cutaway blanket bog; nutrient poor)	Site specific	151	4
	Tier 1	422	2
Blackwater (industrial cutaway raised bog; nutrient rich)	Site specific	100	7
	Tier 1	224	3
Moyarwood (cutover raised bog; nutrient poor)	Site specific	135	5
	Tier 1	462	1

CE, cost-effectiveness.

Either EFs were sourced empirically at each site (derived from the long-term monitoring studies) or Tier 1 default values were taken from the IPCC Wetlands Supplement (2014a) for the appropriate management (drained/rewetted) and nutrient (rich/poor) category under the temperate climatic zone.

a reduction of 224 t CO_2-e ha^{-1} using the Tier 1 EF value. The cost-effectiveness values for this site range between €7 and €3 per tonne of CO_2-e avoided (Table 5.2).

Moyarwood

The situation in Moyarwood differs from that in the previous two cutaway bogs, as this site was drained intensively with the purpose of industrial peat extraction but the site was used only for domestic peat extraction (face banks on the edges of the bog). Rewetting this site consisted of blocking drains with peat dams at regular intervals. The rewetted site was a sink of CO_2 and a high source of CH_4 during the 4-year monitoring period. Therefore, over the 50-year period, the rewetting intervention would reduce CO_2-e emissions from 287 to 152 t CO_2-e ha^{-1}. This reduction (135 t CO_2-e ha^{-1}) is low compared with the Tier 1 value of 462 t CO_2-e ha^{-1}. The cost-effectiveness values for this site range between €5 and €1 per tonne of CO_2-e avoided (Table 5.2).

Overall, rewetting industrial cutaway and cutover bogs corresponded to an average cost-effectiveness value of just under €4 per tonne of CO_2-e avoided, which would clearly support such a mitigation effort.

5.2.3 CEA of paludiculture on cutaway/cutover and grassland sites

Cost

Rewetting interventions at various Bord na Móna cutaway and cutover bogs have more or less successfully restored the hydrological function of natural peatlands (Renou-Wilson *et al*., 2018b). Typically, these sites are often located in a large, flat landscape, which aids in the restoration of groundwater table levels close to the surface. The rewetting costs can therefore be deemed very low because of (1) the scale of preparation of the land (Bord na Móna has machinery *in situ*); (2) the hydrological conditions (either drainage pumps were switched off to allow the WTL to rise naturally or bunds were built over large flat areas to “plumb” the site); (3) the climate (rewetted bogs in the west of Ireland benefit from a very wet climate and no irrigation was deemed necessary in comparison with the German rewetting project); and, finally, (4) ownership of the land (Bord na Móna operates on public land). In addition, rewetting can have objectives beyond simple rehabilitation. It can also be used in combination with other management practices suited to saturated peat soils, such as paludiculture. Paludiculture can be associated with agriculture (e.g. reed farming) or forestry (e.g. alder carr), all of which have in common the critical parameter that the mean WTL is raised to near (but not necessarily at) the soil surface. This has several advantages: GHG emissions are reduced but productive outputs can also help to reduce other GHG sources (e.g. biofuels), as well as providing other ecosystem services (IPCC, 2014a; Joosten *et al*., 2015). Several rewetting projects across Europe and Canada have aimed to establish such “paludiculture” systems on rewetted bogs or fens, especially *Sphagnum* farming (Glatzel and Rochefort, 2017). The cost associated with these rewetting projects has been found to be much higher than those incurred by Bord na Móna, e.g. the establishment of *Sphagnum* culture on bog grassland or cutover bog in Germany would cost between €8.35 m^{-2} and €12.80 m^{-2} (Wichmann *et al.*, 2017).

When analysing these costs, one can separate the "rewetting" only-related costs. These usually include preparation of the area and involve blockage of drainage with additional costs associated with irrigation, water and soil analysis and maintenance of the irrigation system for the duration of the project. Such costs have been acquired from a recently rewetted cutover/grassland site in Germany owned by Klasmann-Deilmann (J. Köbbing, 2016, personal communication) (Table 5.3). These costs can be considered for more "complex" rewetting projects and, although such a high level of expenditure may be not warranted in Irish conditions, its use in the analysis of cost-effectiveness of Irish rewetting projects would shed some light on comparable future enterprises surrounding rewetted peatlands. Using the German costs, it was calculated that, over a 50-year period, the PVC would accrue to €23,500 ha^{-1}.

CO_2/CH_4 emissions/removals

The latest published data from long-term-drained German sites show that GHG budgets were surprisingly variable and much higher than those in Irish published data. The site average emission of 29.2 t CO_2-e ha^{-1} is slightly higher than the Tier 1 EF. Similarly, rewetted study sites in Germany demonstrate highly variable GHG fluxes depending on initial conditions and site types, especially for CH_4 fluxes (Drösler *et al.*, 2013). Rewetting projects in fen ecosystems are reported to save 17 t CO_2-e ha^{-1} yr^{-1} (Günther *et al.*, 2015). With the prevalence of nutrient-rich sites in Germany, we used Tier 1 CH_4 and CO_2 EFs for rewetted nutrient-rich sites for this analysis, giving an average reduction of 24 t CO_2-e ha^{-1} yr^{-1}. Thus, over a 50-year period, a German rewetted bog would reduce emissions by 1132 t CO_2-e ha^{-1} yr^{-1} and, using the associated cost, the cost-effectiveness value is €20 per tonne of CO_2-e avoided (Table 5.4).

Table 5.3. Costs (€) of rewetting an experimental bog in Germany for paludiculture (Klasmann-Deilmann)

Rewetting of degraded peatlands	Cost (€) (ha^{-1})
Preparation of area (inc. irrigation system)	Year 1: 8900
	Year 2: 1300
	Year 3: 600
Maintenance – irrigation	500 per year

In Ireland, nutrient-rich organic soils both under grassland and for peat extraction are known as hotspots of CO_2 and have been identified as targets for rewetting as a strategy to mitigate their large emissions (Renou-Wilson *et al.*, 2014). Therefore, we ran a CEA for a rewetting intervention for paludiculture over these main land use categories: peat extraction and grassland (nutrient rich and nutrient poor). For comparison purposes, only Tier 1 EFs were used.

Over the 50-year period, rewetting a range of peatlands would give cost-effectiveness values between €27 and €105 per tonne of CO_2-e avoided (Table 5.4). Rewetting grasslands appears to be the most cost-effective in terms of climate mitigation measures. However, Irish site-specific (Tier 2) data have shown that emissions from drained grasslands are not as high as the Tier 1 values and therefore cost-effectiveness values would range between €125 and €175 per tonne of CO_2-e avoided for nutrient-poor and nutrient-rich grasslands, respectively (Table 5.4).

Table 5.4. Summary comparison of CE in euros (€) per tonne of CO_2-e avoided of rewetting various peatland land use categories for a 50-year period for paludiculture

Site name	50-year avoided emissions (CO_2-e ha^{-1})	CE (€ per t CO_2-e)
German bog (paludiculture)	1132	20
Cutaway/cutover (nutrient rich)	224	105
Cutaway/cutover (nutrient poor)	462	50
Grassland (nutrient rich)	825	28
Grassland (nutrient poor)	878	27

CE, cost-effectiveness.

Either EFs were sourced empirically at each site (Irish studies) or Tier 1 values were taken from the IPCC Wetlands Supplement (IPCC, 2014a) for the appropriate management (drained/rewetted) and nutrient (rich/poor) category under the temperate climatic zone.

In both grassland site examples, the intervention to mitigate CO_2 emissions must be cautiously appraised because changing practices often results in initial revenue loss, as the landowners in these cases are private farmers who would incur additional costs because of a change in agricultural practices on such land (i.e. forgoing "conventional farming"). Such costs would be related to, inter alia, loss of subsidies, loss of income from livestock and silage sales and fragmentation of lands. The cost of rewetting may also be close to the costs encountered in the German case study, as surrounding landowners (presumably also farmers) may not wish to rewet their land and therefore flood prevention would be required as well as engineering drain blocking and bunds. On the other hand, there may be more opportunity for revenue from paludiculture (growing hydrophilic crops without affecting the C sink potential) and governmental subsidies for such mitigation measures. The economic potential for such measures would require marginal abatement cost curve analysis carried out on representative farms together with in-depth economic knowledge of managing multi-functional lands. This agenda was highlighted in the COP 21 Paris Agreement (UNFCCC, 2018) and the Global Symposium on Soil Organic Carbon (FAO, 2017) and it points to the need for further analysis of policies to better guide peat soil management to help mitigate climate change.

6 Implications for Climate Change Mitigation Measures on Peatlands

6.1 Are Irish Peatlands Climate Proof?

The results of the climate change simulation scenarios in this study highlight the extreme vulnerability of degraded (drained and rewetted) Irish peatlands to even modest changes in climate (i.e. 1–2°C increase in temperature, reduced summer precipitation). We show that drained agricultural peat soils would become the largest hotspots of CO_2 emissions. At the four experimental locations, the rewetted areas released less CO_2 emissions than their drained counterparts, with some vegetation communities likely to remain sinks of atmospheric CO_2 under moderate climate changes. Although rewetting would appear to offer a buffer to some of the largest increases in CO_2 emissions projected for drained areas at most sites, sites that are currently CO_2 sinks are projected to become CO_2 sources in response to new climate stressors. It is also likely that the longer the delay in rewetting, the less likely it is that degraded peatlands will recover their C sink function. Current methods of rewetting may need to be reconsidered or supplemented by management options in order to maintain the necessary WTL for the areas to remain as C sinks.

However, it should be noted that the simulation approach adopted in this study does suffer from some shortcomings. Firstly, as a robust relationship between rainfall input and subsequent WTL has not been established in the literature (or in this study), our choice of a –10 cm decrease and a +5 cm increase in WTL as proxies for reduced summer and increased winter precipitation may seem somewhat arbitrary but are underpinned by field observations in the long-term sites used in this study (Wilson *et al*., 2013a; Renou-Wilson *et al*., 2018a). Secondly, we are cognisant that we have not fully captured the complex interaction between all climate variables, e.g. we have not modified PPFD in our datasets to account for days with a higher cloud cover when simulating increased precipitation. This could lead to an overestimation of GPP on those occasions and consequently an underestimation of annual emissions. Thirdly, we have not accounted for the changes in GPP (and species displacement) potentially produced by higher atmospheric CO_2 concentrations in the future, warmer temperatures and lower/higher WTL. Finally, we were not able to simulate future climate changes on the near-natural site at Glencar because of a lack of access to the data collected over the 11-year GHG monitoring period.

However, IAV in annual NEE across all long-term natural peatland GHG monitoring sites is relatively small and remarkably similar (Figure 6.1), thereby suggesting that these mature sites are more resilient to changes in climate inputs than drained and rewetted sites (Wilson *et al*., 2016b). However, experimental studies have also shown that, under more "extreme" conditions of climate warming, even natural sites may become net C sources (Welker *et al*., 2004; Chivers *et al*., 2009; Laine *et al*., 2009; Wu and Roulet 2014). We should also report the lack of long-term published data from forested peatlands that has prevented such analysis. Given the complexity of climate change impact on tree species in synergy with the affected peat, this land use category requires further attention.

Investigating the sensitivity of peatlands to these scenarios has enhanced our understanding in regard to their vulnerability and in turn will provide a basis for developing appropriate management responses. Such vulnerability assessment informs adaptation planning by identifying climate-related threats (hotspots) and resulting interventions in a context of real peatland scenarios. This study further informed the range of mitigation and adaptation measures already identified for peatlands under future climate change (Table 6.1). It has also highlighted the importance of addressing synergistic factors for assessing vulnerability including changes in management practices in combination with climate change scenarios.

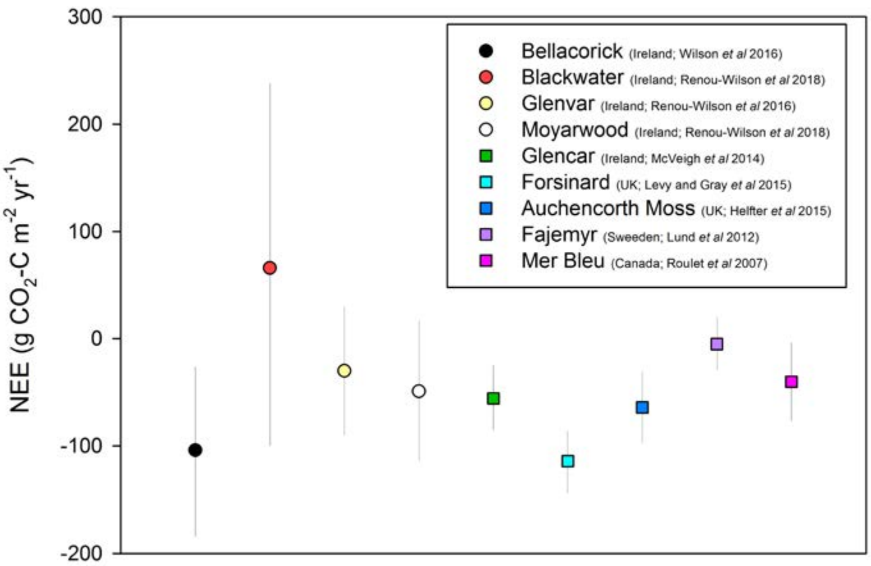

Figure 6.1. Mean annual NEE (g CO_2-C $m^{-2} yr^{-1}$) at peatland sites in the temperate climate zone with long-term (≥4 years) annual CO_2 datasets. Error bars are standard deviations (SDs) of the means. Circles represent rewetted sites and squares represent intact/semi-intact peatland sites. Negative values indicate CO_2 flux from the atmosphere to the peatland (sink).

6.2 Feasible Intervention Strategies Vis-à-vis Current Peatland Status and Distribution, Policies and Impact on Ecosystem Services

6.2.1 International background

The unsustainable management of wetlands is an on-going worldwide environmental issue with “40% of wetland habitats lost over the last 40 years” (Dr Chris Brigg, Irish Ramsar Conference, Co. Monaghan, personal communication, May 2015). The current state of Irish peatlands and the consequences of widespread degradation in terms of loss of various ecosystem services have been highlighted by previous EPA-funded research (Renou-Wilson *et al*., 2011; Wilson *et al*., 2013b), thereby establishing a framework for the development of the first National Peatland Strategy. Peatland degradation globally releases approximately 2000–3000 Mt of CO_2 to the atmosphere annually (Joosten *et al*., 2012), whereas emissions from Irish managed peatlands and related activities (combustion of peat for energy, horticulture) are estimated at c. 3 Mt of C each year (Wilson *et al*., 2013b). However, it is clear that decisions on land use are often made without knowledge regarding their climate impacts and represent barriers to the implementation of appropriate climate change mitigation measures (Regina *et al*., 2015).

Most natural resource planning, management and monitoring methodologies in place today are based on an assumption that species distributions and ecological processes will remain relatively stable over time. This fundamental assumption has been challenged, however, in the face of rapid climatic changes that are altering key ecosystem drivers. For example, two key pieces of EU legislation of particular relevance to Irish peatlands, namely the Habitats Directive (92/43/EEC) and the Water Framework Directive (2000/60/EC), mostly ignore additional pressures arising from climate change in their frameworks. Consequently, the cost-effectiveness and ultimate conservation objectives of such legislation may be dampened.

The Fifth Assessment Report of the IPCC highlighted the importance of peatlands and stated that peat soils contain considerable quantities of C, more than twice the amount currently in the atmosphere, and that climate change may expose these to further degradation, changing their GHG balance

Table 6.1. Projected impacts on Irish peatlands and associated mitigation and adaptation options

Changes in climatic variables	Impacts	Mitigation options	Adaptation options
Temperature	Changing vegetation patterns[a] Northern species such as *Saxifraga nivalis* will probably lose a significant part of their distribution as a result of temperature increase[b] Inability to adapt quickly may threaten many species in peatlands that cannot compete with more adapted and competitive species → loss of biodiversity Higher temperature means longer growing season, especially in the north-west and at high elevation, which increases plant production (via higher PPFD) but also results in higher decomposition if water table drops → response from nutrient-rich peatlands may be more dynamic than that from nutrient-poor peatlands, and degraded or rewetted peatlands are more at risk[c]	New vegetation assemblages may be suited to C sequestration but at the cost of biodiversity loss[d] Rewetting is the first action to mitigate higher temperature impacts to prevent further decomposition while possibly enhancing productivity	Maintenance and conservation of wetlands[e] Fully protect all the remaining raised bog habitats that are near intact or degraded but still capable of natural regeneration[a]
Precipitation: lower rainfall	Areas most affected will be those that have the greatest changes in both precipitation and temperature such as the basin peat of the Midlands[a] Projected loss of climate space at the southern edge of the distribution is indicated for degraded raised bogs[f] The projected available climate space for active blanket bog is regionally sensitive to loss, notably for lower lying areas in the south and west[f] → severe diminution of natural Irish peatland cover by 2075[g] Dry periods will lead to water level drawdown, affecting short-term C sequestration potential[h] but also long-term loss of stored peat Long periods of low precipitation may increase the risk of bog fires, especially in drained and degraded peatlands → positive feedback loop leading to more C in the atmosphere	Rewetting drained or abandoned peatlands is critical to stop further release of C via decomposition and fires Protect more areas in northern part of the country to avoid future mismanagement	Reducing the vulnerability of peatlands by a substantial programme of drainage, blocking and wetting or rewetting[i]
Precipitation: higher frequency and/or intensity	Increased precipitation could lead to more optimal conditions for C sequestration[h] but intense rainfall could enhance peatland erosion in susceptible areas[a] Increased level of cloudiness could promote peatland occurrence (low potential evaporation thus keeping the ground wet) but keep C accumulation rates low (low amount of sunshine)	Restoration of the vegetation cover on all peatlands is critical to prevent wind and rain erosion and further C losses	Maintenance and conservation of wetlands[e] Restoration of bare peat areas[i]

[a]**Renou-Wilson *et al.* (2011).**

[b]**Malone and O'Connell (2009).**

[c]**Wilson *et al.* (2016b).**

[d]**Renou-Wilson *et al.* (2018a).**

[e]**IPCC (2013a).**

[f]**Coll *et al.* (2014).**

[g]**Jones *et al.* (2006).**

[h]**Laine *et al.* (2009).**

[i]**Renou-Wilson *et al.* (2018b).**

(IPCC, 2013). A major European research programme concluded that "The most effective option to manage soil carbon in order to mitigate climate change is to preserve existing stocks in soils, and especially the large stocks in peat and other soils with a high content of organic matter" (Schils *et al*., 2008). International biodiversity and climate change conventions (Convention on Biological Diversity and United Nation Framework Convention on Climate Change) now recognise peatlands as a priority for action, with peatland restoration being identified as "low-hanging fruit" in tackling climate change. At the national level, the Climate Action and Low Carbon Development Bill (Houses of the Oireachtas, 2015) has identified the establishment of legally binding GHG emissions targets (following EU targets) as a key priority for the transition to a low C economy. This should be achieved through a significant lowering of emissions but also through the possibility of C sinks such as forests and bogs. It also specifically seeks to incorporate scientific knowledge relating to climate, together with integration across relevant governmental departments, to develop robust adaptation strategies.

6.2.2 Integration vulnerability assessment

Vulnerability to climate change refers to the degree to which an ecosystem is likely to experience harm as a result of changes in climate (Schneider *et al*., 2007). Understanding all the complex interrelated components of vulnerability is therefore central to identifying adaptation needs and developing adaptation policy. In the context of advancing actions on climate change currently in progress (EPA, 2014), the emerging field of "climate change impacts and adaptation" refers to the process of identifying strategies to prepare for the impacts of climate-related threats and stresses on (in this instance) the unique biological natural resource that are peatlands. Climate change adaptation requires an understanding of how climate change may impact on a given biological system so that appropriate management strategies can be identified. By understanding the links between climate, hydrology, ecology and GHG dynamics in natural and managed Irish peatlands under a range of driving pressures, we mapped an integrated vulnerability assessment (associated exposures, sensitivities and resilience) together with adaptation options (Figure 6.2). Such assessment of the potential impacts of future climate change on peatlands combined with other stressors, such as land use changes, is of interest to a wide range of stakeholders from site managers to policymakers across many departments (energy, environment, agriculture, forestry, etc.).

Adaptation can result in a range of outcomes, one of which is "resilience" or the capacity to maintain existing system structure and function. Peatlands are a prime example in which maintaining and enhancing the resilience of these natural ecosystems can be the best and most cost-effective defence against climate change (IPCC, 2014b).

6.2.3 Strategies for Ireland

Although we should be cautious comparing the cost-effectiveness of rewetting peatlands with that of other more established methods of mitigation, our datasets and real cost scenario make for a robust appraisal that can be compared with other local interventions. Although these are limited in Ireland, cost-effectiveness values for bioenergy production, presented as a relatively cost-effective option, at least in Europe, have been calculated in the UK to be between €300 and €7800 per tonne of CO_2-e avoided (Bailey, 2013). Rewetting industrial cutaway peatlands offers a much more cost-effective method on a similar land area basis.

Our analysis shows that rewetting large-scale industrial cutaway/cutover peatlands should be unquestionably a priority action for Ireland, as it will reduce GHG emissions in a very cost-effective manner (see Table 5.2). Secondly, given the high emissions from deep drained grasslands, such interventions can also be very cost-effective, even with the high initial cost of rewetting, provided the economics associated with land use change are beneficial for the farmers. Rewetting is the first step towards a possible new sustainable use of peatlands through paludiculture and/or other valued ecosystem services (biodiversity/recreation). A network of rewetted peatlands across Ireland has already demonstrated the climate and biodiversity benefits of rewetting certain degraded peatlands, recommending certain land use categories to be prioritised for immediate rewetting in order to maximise biodiversity provision and climate change mitigation (Renou-Wilson *et al*., 2018b). Studies in the UK have demonstrated that the long-term benefit of peatland rewetting and restoration for some specific

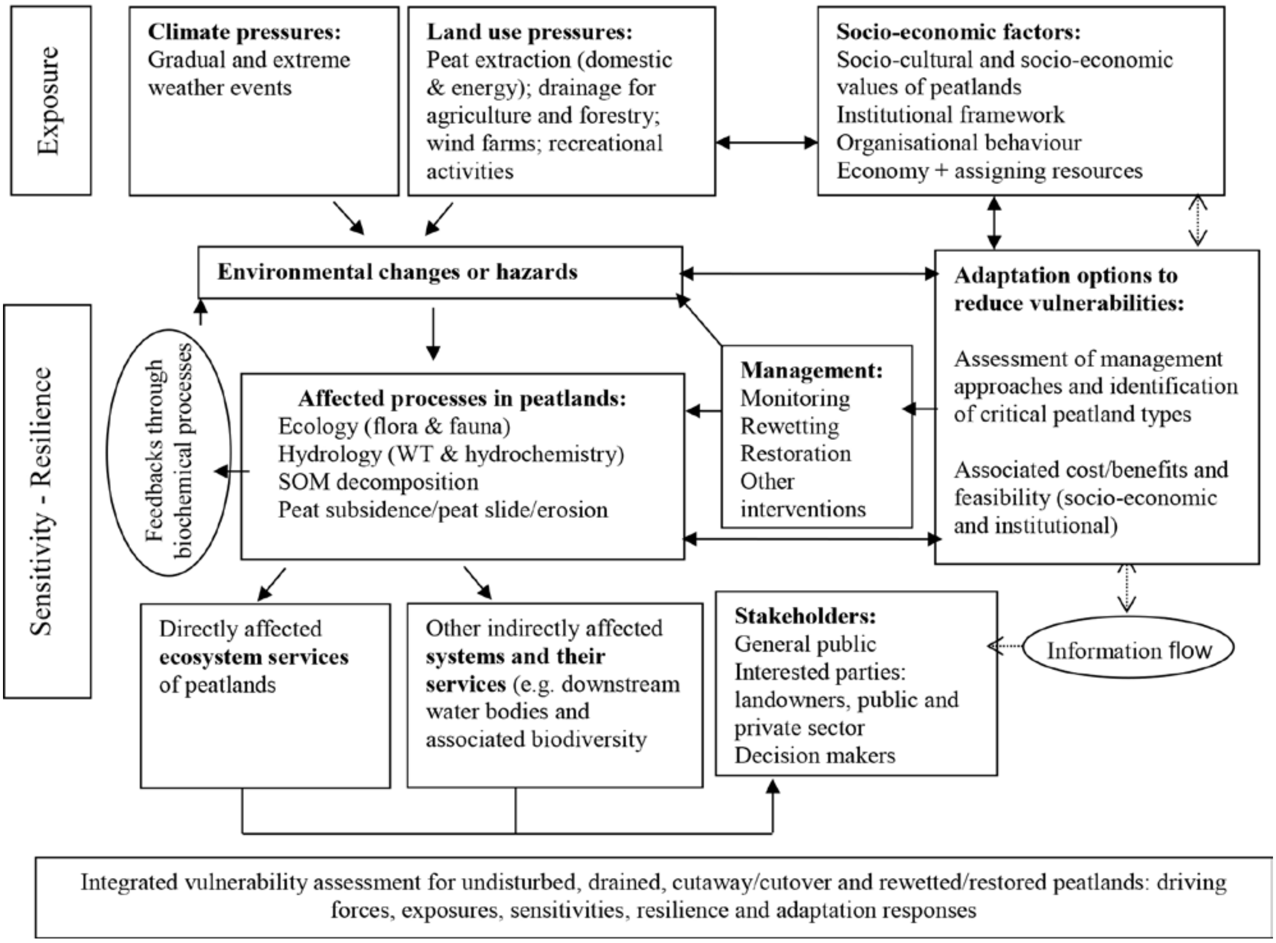

Figure 6.2. Integrated vulnerability assessment of natural and managed peatlands under a range of driving pressures and associated exposures, sensitivities and resilience, together with adaptation responses. WT, water table.

ecosystem services, such as improvement of water storage and quality, has the potential to balance the high financial investment (Grand-Clement *et al*., 2013). Positive results have already been demonstrated in Germany, for example where the full suite of ecosystem services was brought back 10 years after the rewetting of a degraded peatland (Zerbe *et al*., 2014). With newly rewetted peatland projects in Germany (MoorFutures; http://www.moorfutures.de) and the UK (The Peatland Code; Reed *et al*., 2014), new tools (standards and technical guidance) are being developed to enable the corporate sponsorship of the rewetting and restoration of peatlands for climate change mitigation, which usually bring additional co-benefits that are not easily monetised (e.g. biodiversity, watershed protection). The continuous development of a rigorous quantification and officially certified recognition system of climate and co-benefits should help develop regional C markets to fund further peatland restoration and rewetting projects (Bonn *et al*., 2014).

Although intervention strategies such as rewetting can be seen as an adaptive response to global climate change with multiple benefits, not least the decrease in C losses from soils in Ireland, their full effect might be affected (either dampened or strengthened) if delayed and as future climate change plays out. For example, predicted higher precipitation in some regions could work in synergy with government-led actions to rewet peatlands and increase biodiversity, thereby restoring most of the ecosystem services provided by those natural systems. On the other hand, stronger or more persistent environmental changes to already affected peatlands (be it from energy or land use policy) may shift these to new ecosystems, which either may lose even higher amounts of C or may compensate for C losses via certain feedbacks (e.g. vegetation, soil subsidence). Paludiculture may be an option to stop such loss of ecosystem services and one that deserves serious investigation in Ireland. More than ever, the cross-cutting issues of peatland management in the future need to be looked at by all relevant governmental departments, agencies and semi-state bodies responsible for policy development. It is envisaged that such studies will directly feed into the Peatlands Strategy Implementation Group whose role is to achieve the objectives of the National Peatland Strategy.

7 Summary of Observations and Recommendations

Although peatlands are considered generally resilient ecosystems over decades and centuries, a significant and more rapid change is expected in GHG dynamics and vegetation composition in the 21st century. The potential impacts of future climate change on peatlands combined with other stressors, such as land use changes, have major implications for our ability as a society to conserve natural ecosystems and manage natural resources such as peatlands. This study points to clear mitigation measures considered the "low-hanging fruit" of climate change policy. Although variations and uncertainty in climate change projections at regional levels are pronounced, preparing for and coping with the effects of climate on these ecosystems – the objectives of climate change adaptation – should now be an overarching framework for conservation, and natural resource management should be of interest to a wide range of stakeholders, from site managers to policymakers.

Long-term GHG monitoring of peatlands has provided robust baseline data that can be used to understand better the effects of climate change on peatland ecosystems.

Observation 1: The results of the climate change simulation scenarios based on long-term datasets and response models highlight the extreme vulnerability of degraded (drained and rewetted) Irish peatlands to even modest changes in climate (i.e. 1–2°C increase in temperature, reduced summer precipitation). However, rewetted areas released less CO_2 emissions than their drained counterparts, with some vegetation communities likely to remain sinks of atmospheric CO_2 under moderate climate changes.

Recommendation 1: It is recommended that a national management plan is established to ensure that a sufficient range of natural and rewetted peatlands are properly managed to maintain the necessary WTLs to sustain as many ecosystem services as possible. Additional rewetting projects should be identified as "low-hanging fruit" mitigation measures.

Observation 2: Drained peatlands managed for agriculture and peat extraction are significant CO_2 emission hotspots and will have a large positive feedback on climate change (large CO_2 emissions with projected climate change).

Recommendation 2: Drained peatlands used for agriculture and peat extraction should be targeted for rewetting as a climate mitigation strategy to prevent an even bigger problem in the future. After-use of cutaway peatlands and abandoned cutover sites should be prioritised to maximise the areas being rewetted.

Observation 3: CEA is a good metric to compare mitigation efforts across climate change policies. The rewetting of industrial cutaway and cutover bogs corresponded to an average cost-effectiveness value of just under €4 per tonne of CO_2-e avoided, which would clearly support such mitigation efforts.

Recommendation 3: The rewetting of industrial cutaway and cutover bogs is a low-cost intervention supporting an immediate and effective mitigation measure.

Observation 4: Although rewetted peat soils have been found to behave like their natural counterparts in terms of CO_2 exchange, they display a much wider range of GHG fluxes. Our results indicate that rewetted sites may be more sensitive to inter-annual changes in weather conditions than their more resilient intact sites and may switch from an annual CO_2 sink to a source if triggered by drier summers. As presented in the IPCC Wetlands Supplement, keeping the C stock in organic soils (by rewetting drained bogs) can be an effective mitigation measure to reduce CO_2 emissions. The Tier 1 default EF values are only screening tools, however. It is critical for Ireland to establish a monitoring network to verify these avoided emissions and accordingly modify potential adaptation options. This is critical to ensure such ecosystem "resilience" within our unique biogeographical region.

Recommendation 4: Continued and expanded long-term monitoring of rewetted sites as well as the promotion of future rewetting projects should be carried out without further delay and in conjunction with potential sustainable productive systems (e.g. paludiculture). Monitoring of rewetted sites in the early stages is of utmost importance as well as investigating new methods of rewetting in order to maintain the necessary WTL for the areas to remain C sinks and promote sustainable management.

Observation 5: Long-term monitoring of natural, degraded, managed and rewetted peatlands in the last 15 years has demonstrated that their C cycling function (GHG dynamics) is already under pressure from climatic variables such as drought, which increase soil temperatures and lower the WTL, thus controlling CO_2 fluxes and CH_4 emissions. This is of great significance for adaptation measures within the climate change policy arena given the important role of peatlands as part of the global C cycle.

Recommendation 5: Monitoring of a range of natural, rewetted and managed peatland ecosystems (in terms of GHG dynamics, vegetation composition) should be implemented to assess their contribution to and their impacts on climate change. Such a "warning system" is warranted in order to anticipate the response of peatlands to climate changes in the short to medium term.

Recommendation 6: For all the reasons above, the response of Irish peatlands to climate change is a fertile area for future research. A variety of rewetted sites should be monitored over many years, collecting high-frequency measurements and capturing spatial hydrology, in particular intensive monitoring of CH_4 and aquatic C losses (DOC and POC) during and after extreme weather events (high precipitation events).

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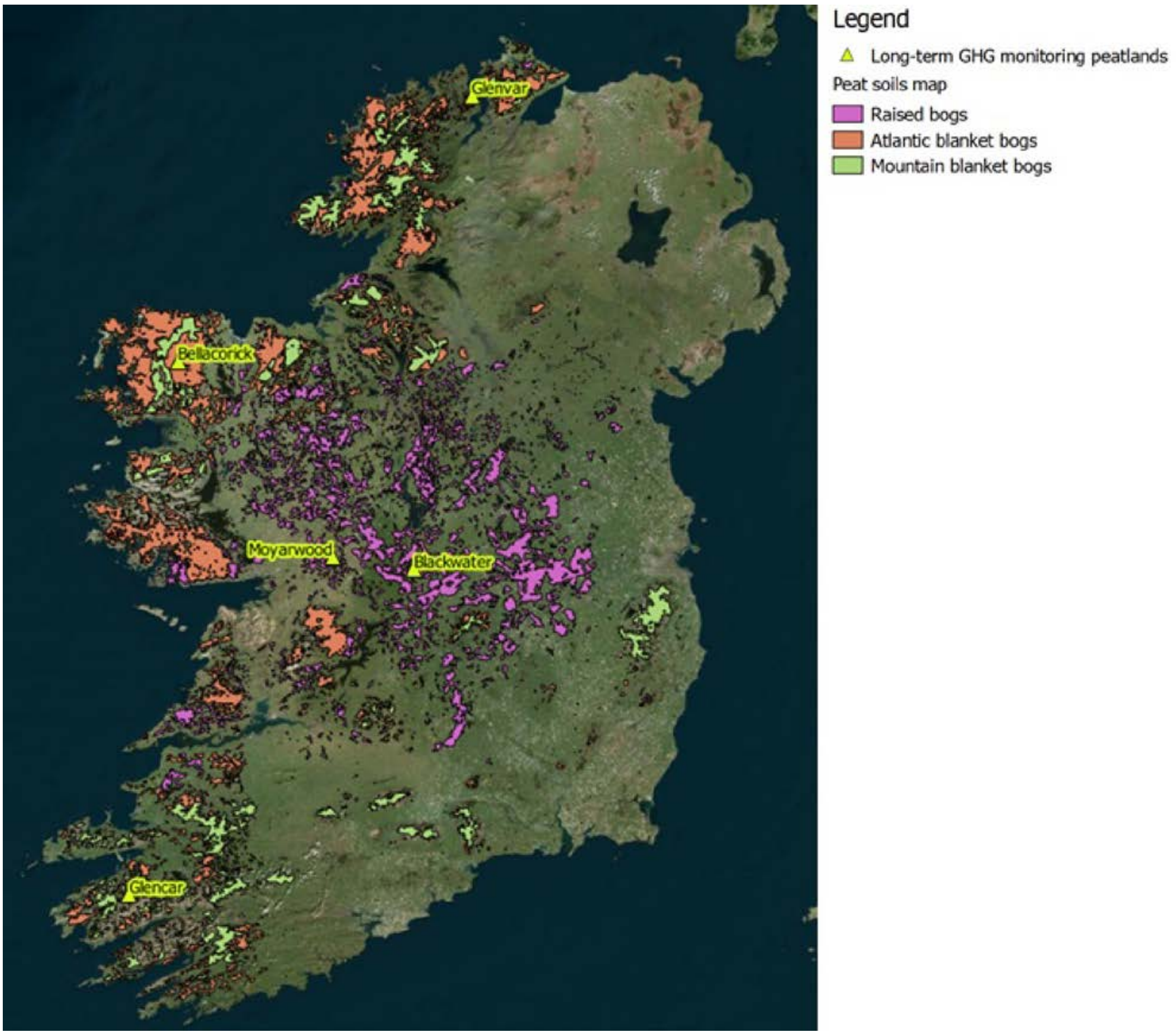
Abbreviations

C	Carbon
CEA	Cost-effectiveness analysis
CH_4	Methane
CO_2	Carbon dioxide
CO_2-e	Carbon dioxide equivalent
DOC	Dissolved organic carbon
EF	Emissions factor
GDP	Gross domestic product
GHG	Greenhouse gas
GPP	Gross primary production
IAV	Inter-annual variation
IPCC	Intergovernmental Panel on Climate Change
K	Hydraulic conductivity
N_2O	Nitrous oxide
NEE	Net ecosystem exchange
POC	Particulate organic carbon
PPFD	Photosynthetic photon flux density
PVC	Present value cost
R_{eco}	Ecosystem respiration
WTL	Water table level

Appendix 1 Location and Further Information Pertaining to Long-term GHG Peatland Sites Monitored in Ireland

Name	Original peatland	Surface peat nutrient status	Prior land use	Restoration/rewetting method	Year of rewetting
Glencar (Ballygasheen), Co. Kerry	Atlantic blanket bog	Poor	Extensive grazing	Natural	Natural
Moyarwood, Co. Galway	Raised bog	Poor	Drained only (BnM) and domestic peat extraction	Peat dams	2012
Blackwater, Co. Offaly	Raised bog	Rich	Industrial peat extraction (BnM)	Cessation of pumping	1999
Bellacorick, Co. Mayo	Atlantic blanket bog	Poor	Industrial peat extraction (BnM)	Peat dams/profiling/bund	2002
Glenvar, Co. Donegal	Organic soil	Poor	Grassland	Lack of drainage maintenance	Since 2000

BnM, Bord na Móna.



Appendix 2 GHG Response Models Used for Scenario Simulation at Each Site and for Various Vegetation Communities and Including Variables Such As WTLs or Soil Temperature

Site type	GHG variable	Model
Bellacorick[a]	GPP	$GPP_{max}\left(\frac{PPFD}{PPFD+k_{PPFD}}\right)*GAI*\left[\exp\left(-0.5\left(\frac{WT-a}{b}\right)^2\right)\right]$
		$GPP_{max}\left(\frac{PPFD}{PPFD+k_{PPFD}}\right)*GAI$
		$GPP_{max}\left(\frac{PPFD}{PPFD+k_{PPFD}}\right)*\left[\frac{GAI}{(GAI+a)}\right]$
	R_{eco}	$a*\exp\left[b\left(\frac{1}{T_{REF}-T_0}-\frac{1}{T-T_0}\right)\right]*\left[\frac{1}{1+\exp\left(\frac{WT-c}{d}\right)}\right]$
		$a*\exp\left[b\left(\frac{1}{T_{REF}-T_0}-\frac{1}{T-T_0}\right)\right]*\left[c+(d*WT)+(e*(WT^2))\right]$
		$(a+(b*WT))*\left[\exp\left(c\left(\frac{1}{T_{REF}-T_0}-\frac{1}{T-T_0}\right)\right)\right]$
		$a*\exp\left[b\left(\frac{1}{T_{REF}-T_0}-\frac{1}{T-T_0}\right)\right]*WT$
	CH_4	$(\exp(a*T_{10cm}))*(b+(c*WT))$
		$(\exp(a*T_{10cm}))*(b+(c*GAI))$
Glenvar[b]	GPP	$P_{max}\left(\frac{PPFD}{PPFD+k_{PPFD}}\right)*\left[\frac{LAI}{(LAI+a)}\right]$
		$P_{max}\left(\frac{PPFD}{PPFD+k_{PPFD}}\right)*\left[\frac{LAI}{(LAI+a)}\right]$
	R_{eco}	$(a+(b*WT))*\left[\exp\left(c*\left(\frac{1}{T_{REF}-T_0}-\frac{1}{T_{5cm}-T_0}\right)\right)\right]*(Ln(LAI)+d)$
		$(a+(b*WT))*\left[\exp\left(c*\left(\frac{1}{T_{REF}-T_0}-\frac{1}{T_{5cm}-T_0}\right)\right)\right]$

Site type	GHG variable	Model
Blackwater/Moyarwood[c]	GPP	$GPP_{max}\left(\frac{PPFD}{PPFD+k_{PPFD}}\right)*GAI$
		$GPP_{max}\left(\frac{PPFD}{PPFD+k_{PPFD}}\right)*\left[\frac{GAI}{(GAI+a)}\right]$
	R_{eco}	$a*\exp\left[b\left(\frac{1}{T_{REF}-T_0}-\frac{1}{T-T_0}\right)\right]*WT$
		$(a+(b*WT))*\left[\exp\left(c\left(\frac{1}{T_{REF}-T_0}-\frac{1}{T-T_0}\right)\right)\right]$
		$a*\exp\left[b\left(\frac{1}{T_{REF}-T_0}-\frac{1}{T-T_0}\right)\right]*VMC$
		$a*\exp\left[b\left(\frac{1}{T_{REF}-T_0}-\frac{1}{T-T_0}\right)\right]*\exp(c*WT)$
	CH_4	$(\exp(a*T_{10cm}))$
		$(\exp(a*T_{10cm}))*(b+(c*WT))$

GAI, Green Area Index; GPP_{max}, gross primary production maximum photosynthesis; k_{PPFD}, PPFD value at which *GPP* reaches half its maximum; *T*, soil temperature at 5 cm depth; T_0, (minimum) temperature at which respiration reaches zero, set here at 227.13 K; T_{REF}, reference temperature set at 283.15 K; WT, water table depth.

***a*, *b* and *c* are model parameters. NEE = GPP − R_{eco}. See associated publications for further details.**

[a]Wilson *et al*. (2016b).

[b]Renou-Wilson *et al*. (2016).

[c]Renou-Wilson *et al*. (2018a).

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.

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Vulnerability Assessment of Peatlands: Exploration of Impacts and Adaptation Options in Relation to Climate Change and

Authors: Florence Renou-Wilson and David Wilson

Identifying pressures

Peatlands have played an important role in climate regulation over the past 10,000 years and the rewetting and restoration of peatlands has been demonstrated to offer considerable climate change mitigation opportunities. However, peatlands and organic soils in general are also vulnerable to climate change impacts and understanding and preparing for the effects of climate change – i.e. adaptation – is now seen as the overarching framework for conservation and land use management. The VAPOR project was established to inform a transition to a climate-resilient Ireland by providing science-based information on the vulnerability of peatlands to climate change, including extreme weather events. Long-term greenhouse gas monitoring studies over the last two decades have shown that Irish peatlands have been impacted by a wide range of environmental conditions. These studies provide robust greenhouse gas baseline data that can be used to better understand the effects of climate change on peatland ecosystems.

Informing policy

The results of the climate change simulation scenarios in this study highlight the extreme vulnerability of degraded (drained and rewetted) Irish peatlands to even modest changes in climate (i.e. 1–2°C increase in temperature, reduced summer precipitation). However, carbon dioxide (CO_2) emissions from rewetted areas were lower than those from their drained counterparts, with some rewetted vegetation communities likely to remain sinks of atmospheric CO_2 even with moderate climate changes. Drained agricultural peat soils are projected to become even greater hotspots of CO_2 emissions.

It is likely that climate change will have significant impacts on all aspects of peatlands, but currently degraded peatlands are most at risk of desiccation, cracking and decomposition, leading to more carbon being released to the atmosphere and to waterways

Rewetting was found to be a climate-proof, effective mitigation strategy, provided that extreme drying events like summer drought are not a more frequent occurrence. Importantly, the longer that a rewetted peatland is established, the more resilient it will be to climate change. A cost-effectiveness analysis supports early rewetting actions as an effective, low-cost mitigation measure.

Developing solutions

With the observations highlighted by this research, it is strongly recommended that a national management plan is established to ensure that a sufficient range of natural and rewetted peatlands are properly managed to maintain the necessary water table levels that will sustain as many ecosystem services as possible. Secondly, drained peatlands used for agriculture and peat extraction should be targeted for rewetting as a climate change mitigation strategy to prevent increased greenhouse gas emissions in the future. Rewetting projects on cutover and cutaway sites (public-owned land) should be identified as a “low hanging fruit” mitigation measure.

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

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

www.epa.ie

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