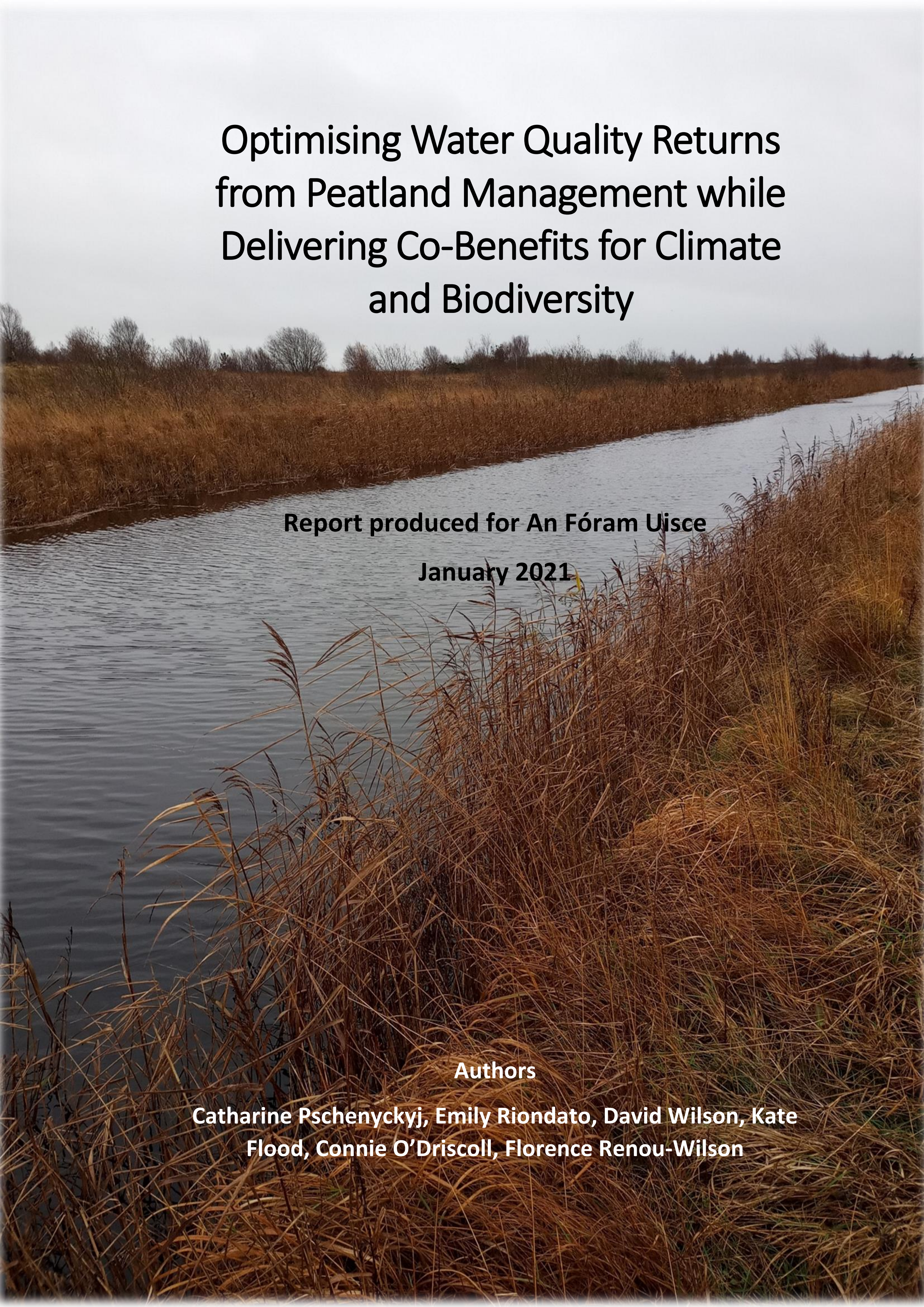


Optimising Water Quality Returns from Peatland Management while Delivering Co-Benefits for Climate and Biodiversity

Report produced for An Fóram Uisce

January 2021

Authors

Catharine Pschenyckyj, Emily Riondato, David Wilson, Kate Flood, Connie O'Driscoll, Florence Renou-Wilson

Table of Contents

List of Tables

List of Figures

Executive Summary

Irish peatlands are of national and international importance. Half of the blanket bogs considered to be of conservation importance in the European Atlantic Biogeographic Region are found on this island, along with some of the last Oceanic raised bog remaining in the EU. Irish peatlands are also a significant carbon store, containing ¾ of the total soil carbon stock in the Republic of Ireland. Healthy peatlands help provide natural filtration processes to clean water and reduce the quantity of water entering rivers and lakes; they help regulate the global climate and mitigate climate change; they support unique flora and fauna; and provide multiple social and cultural services to society.

However, just 18% of the 1.4 million hectares of peatlands are 'near-natural' or 'healthy'. The remaining 82% of our original peatlands (1.2 million ha) have been degraded or drained from activities associated with domestic and industrial peat extraction, agriculture and commercial forestry. Degraded peatlands negatively impact water quality, and release nitrous oxide and CO_2 to the atmosphere, sediment and nutrients to water courses, and lead to a reduction in biodiversity. Peatland degradation has been identified as a common contributory factor in the unfavourable status of many water-dependent habitats and species; and peat extraction is a significant pressure acting on many Irish water bodies.

This report was produced for An Fóram Uisce to provide guidance on how peatland management can be reimagined in order to optimise water quality improvements, while delivering co-benefits for climate change and biodiversity. This study was split into five key work packages: 1) Rewetting degraded peatlands; 2) carbon cycling in intact, degraded and rewetted peatlands; 3) Cultural ecosystem services and social values of peatlands; 4) Alternative management options for degraded peatlands; and 5) strategic guidance and resources for integrated peatland management.

1. Rewetting degraded peatlands

Work package 1 is a review of national and international literature relating to the effects of drainage and rewetting of peatlands, with a focus on water quality impacts, as well as greenhouse gas (GHG) emissions and biodiversity. Studies show concentrations of nitrogen, phosphorus, base cations, heavy metals, DOC and particulate organic carbon (POC) are increased with drainage, although this depends on site-specific characteristics and management. However, rewetting results in long term decreases of inorganic nitrogen, base cations, suspended solids and DOC, as well as increasing biodiversity and the carbon sequestration potential. In addition, degraded peatlands may have significantly higher nitrous oxide emissions (a greenhouse gas), whilst rewetted organic soils have decreased emissions.

Rewetting is an important management technique to improve water quality, reduce GHG emissions, improve carbon sequestration, and promote biodiversity, and other restoration techniques, such as reseeding, can speed up revegetation and these improvements.

2. Carbon cycling of natural, degraded and rewetted peatlands

Work package 2 reviews carbon cycling in drained and rewetted peatlands with a comparison with observations from natural peatlands, including gaseous and fluvial carbon dynamics, using data from studies based in Ireland and the United Kingdom. Natural peatlands have a high water and reduced decomposition rates, leading to an accumulation of dead plant material and organic matter, and the carbon contained therein. However, studies have shown that drainage has a fundamental impact on the carbon that is stored in the peat Figure 6and the peatland invariably switches from acting as a long-term CO_2 sink to a large CO_2 source, as well as releasing more waterborne carbon (DOC). In contrast, rewetting has been shown to reduce CO_2 emissions and DOC concentrations, although methane emissions may increase. Finally, Irish peatlands are likely to be severely affected by climate change, including changes in decomposition rates leading to a loss of the carbon stored; increased fire risk; and reduced peatland area. Degraded peatlands are also expected to be more vulnerable to climatic changes.

3. Cultural ecosystem services and social values of peatlands

The third work package provides a detailed overview of cultural ecosystem services and social values of peatlands, with a review of the services and disservices provided in Ireland. Cultural ecosystem services are an important category of benefits that people gain from natural environments, such as peatlands, and should be considered in policy and decision-making alongside other ecosystem services at national, regional, and local scales. The assessment and valuation of cultural services requires engaging with a range of stakeholders, through participatory processes that enable expression of a broad range of values. Currently in Ireland, there is a shift in cultural values and societal norms around the uses and value of peatlands. Traditionally, economic and utilitarian values relating to extraction of peat had the most value for companies like Bord na Móna and communities living beside peatlands. However, cultural aspects, such as recreation, tourism, and heritage are increasingly considered of value by emerging community groups as peatlands transform to sites of restoration, recreation, and conservation. These shifts in values from unsustainable use of peat to management for biodiversity and ecosystem services, are largely positive and supportive of sustainable peatland management.

4. Alternative management options for degraded peatlands

Work package 4 reviews current and alternative management options for different peatland uses (extraction, forestry, and agriculture) in terms of reducing negative impacts on the environment. Current management interventions for peat extraction include silt ponds, rehabilitation and reclamation for new land uses. Rewetting is not required under licencing for rehabilitation and revegetation occurs through natural succession. Typically, vascular plants rather than bog indicator species return, even after a 30-year period. Restoration prescribes increasing the water table to within 10 cm of the surface and offers the best long-term water quality benefit, in addition to climate change and biodiversity benefits. Alternative land use with rewetting is the optimum solution for industrial peat extraction, and where unfavourable site modifications could not support restoration, new habitat types are proposed, such as mosaics of bog/fenland, woodland, heather and scrub/open areas. It was also concluded that industrial cutaway peatlands are not suitable for raw water storage as reservoirs. Other techniques that offer potential for water quality improvements include biochar filters, overland flow, constructed wetlands and chemical purification.

5. Strategic guidance and resources for future integrated management of peatlands

The final work package provides strategic guidance, which is split into four key priority areas, and identifies where resources are needed for implementation.

Priority 1- Including social values in peatland management and enhancing stakeholder collaboration

Aim: To enable social values and perspectives to be identified, assessed and included in peatland management and decision making, and lift barriers by enabling collaboration between stakeholders.

☞Incorporate social and cultural values into research, policy, and decision-making

- Interdisciplinary and transdisciplinary research:

  R 1.1*: Encourage the inclusion of research from social sciences, humanities, and the arts alongside economic and ecological disciplines when commissioning research to guide conservation and sustainable management of peatlands.*

- Co-production of knowledge:

  R 1.2*: Develop shared knowledge of different areas of expertise at all stages of projects and co-develop research objectives, methods and outputs from the start.*

☞Identify evidence gaps and encourage research on Cultural Ecosystem Services (CES) and social values of peatlands

- Data, inventories, and monitoring of CES of peatlands:

  R 1.3*: Identify potential data sources to support mapping of CES of peatlands and generate new sources where necessary.*

- CES Indicators:

  R 1.4: Identify suitable indicators for CES of peatlands so results of assessments and valuations can be communicated to decision makers and practitioners in conservation management.

- Research on the impact of restoration, rewetting, or ongoing degradation of peatlands on the provision of cultural services:

  R 1.5*: Identifying whether the ecological state of peatland ecosystems positively or negatively affects the delivery of cultural services, and differences in provision of CES in different types of peatland habitat e.g. coastal blanket bogs, raised bogs and industrial cutaway.*

☞Enhance collaboration with all stakeholders

Established organisations with the power to facilitate networking and knowledge sharing should be identified and tasks with specific remit in order to contribute to the delivery of the key recommendations below.

- Collaboration between stakeholders:

  R 1.6*: A map of Irish peatland stakeholders has been initiated and should be published and shared with the public as a basis for further stakeholder analysis and improved collaboration: the map is available here for comments:* https://adobe.ly/3uaAfQV

  R 1.7*: Conduct a stakeholder analysis to identify key collaboration pathways, assess the quality of stakeholder relationships and recommend new areas for collaboration.*

  R 1.8*: Create new and support existing networks and bridging organisations.*

  R1.9*: Ensure meaningful engagement and participation early in the collaborative process.*

  R1.10*: Stakeholders should engage in collaborative actions including awareness raising; advice, training, and knowledge transfer; and building a common platform, such as a National Peatland Group.*

- Stakeholder research collaboration:

  R 1.11*: Priority should be to widen the sources of funding in order to establish long-term monitoring, which is typically lacking around restoration projects as funded research projects are always limited in time. Funding for researchers to train communities and practitioners is critical to enable transfer of skills, as well as efficiently communicating the science to the public. Finally, a new model of co-designed research that integrates citizen science must be developed to provide a bottom-up, place-based perspective to peatland research.*

☞Develop mechanisms to support inclusive and collaborative governance and encourage bottom-up approaches to integrated peatland management

The following recommendations can help to support sustainable management of peatlands at community level:

R 1.12*: Build local community capacity in understanding, monitoring and assessment of peatlands through training, citizen science initiatives and knowledge exchange.*

R 1.13*: Develop structures and supports for community groups applying for funding.*

R 1.14*: Develop strong partnerships between state agencies and community groups and networks in an open, transparent, two-way process of information sharing. The Community Wetlands Forum provides a platform and advice for developing such partnerships, and Public Participation Networks (PPN) could also be better utilised to provide guidance and funding to community environmental groups.*

R 1.15*: Encourage public sector organisations to have dedicated community liaison staff with expertise in community engagement and knowledge of participatory approaches to conservation.*

R 1.16*: Encourage action research approaches, i.e. research that is initiated and driven by communities, and where communities are involved with researchers in all aspects of the research process.*

R 1.17*: The need for integrated rather than single-value approaches to ecosystem assessment and valuation, which combine ecological, cultural, economic, and ethical value dimensions, is increasingly advocated* (Díaz et al., 2020, Jacobs et al., 2016).

Priority 2- Identify land use/ land use change impacts and co-benefits of management options

Aim: to provide an accurate understanding and coherent vision of peatland utilisation, their impacts and the available choices.

☞Embed each peatland management decision within an overview of peatland utilisation options, impacts and co-benefits

***R 2.1:** It is recommended to identify and disseminate scientific facts about peatlands pertaining to each management decision in order to provide a coherent vision of the range and extent of peatland utilisation and known impacts on key ecosystem services, such as climate, biodiversity, water and socio-cultural.*

Priority 3- Implement existing policies and ensure full compliance with relevant regulations

Aim: to prevent deterioration of water quality and apply adequate mitigation measures. The case for the sustainable integrated management of peatlands is underpinned by existing legislation whose compliance directly bears on the development and outcome of the sustainable management of peatlands. Compliance with existing regulations with the eradication of deficiencies or conflicts in these legislations must be improved as a first approach to integrated peatland management in Ireland, and recommendations in relation to different types of governance is presented below.

☞Conservation/biodiversity governance

***R 3.1**: To urgently meet the objectives for designated protected peatlands under the Habitats Directive and restore all raised and blanket bogs SAC.*

***R 3.2**: To provide sufficient funding via new funding mechanisms for peatland restoration schemes, which include long term monitoring, support for peatland community schemes and promotion of citizen science.*

☞Environmental governance

***R 3.3**: Finalising the legal status of all peat extraction activities together with the implementation of evidence-based mitigation measures.*

☞Agricultural and forestry governance

***R 3.4**: Rewetting of nutrient rich organic soils that act as hot spots of both CO_2 and N_2O should be prioritised.*

***R 3.5:** Incentives are required to rewet agricultural peat soils.*

***R 3.6**: Ireland must look at the combination of new CAP instruments that are now available, which could pave the way toward low-emission peatland utilisation to satisfy the need of a range of stakeholders.*

***R 3.7**: Decisions on future land use must be site-specific accounting for the full suite of ES and demonstrate a clear regard for sensitive receptors.*

☞Water governance

__R 3.8__: Peatland degradation status should be fully recognised in the River Basin Management plans and thus monitored carefully in all catchments, especially with regards to DOC and ammonia emissions within each catchment.

Priority 4- Investigate the current and future risks; monitor actions; and research alternatives

Aim: to identify gaps in knowledge, monitor existing actions and research alternatives to better inform decision

☞Environmental and land use research

R 4.1: Key research questions pertaining to land use and land use change affecting peatlands including windfarms, forestry and agriculture should be carefully scoped out, compiled and prioritised.

R 4.2: An Ecosystem Approach (used to improve ecological impact assessment) should be called upon to set up the next research priorities in relation to peatlands.

☞Long-term monitoring and datasets repository

__R 4.3__: Tracking the success of interventions for integrated peatland management (e.g. long term monitoring of key performance indicators following rewetting schemes) is critical to develop robust guidance.

__R 4.4__: As a priority, a compendium of Irish restoration/rewetting projects and peatland datasets should be available to all stakeholders.

__R 4.5__: Development of a standardised methodology and training capacity that enables individual peatland sites to be consistently monitored, thereby creating a network of comparable sites.

__R 4.1:__ Establish a national peatland observatory / research site network to support long-term research and initiate large scale pilot studies/catchment interventions; in conjunction with a common research protocol (definition, field measurements etc.).

☞Innovative sustainable management options

__R 4.7:__ New, well-designed experimental plots with replications should be established and monitored over minimum four years at various peatland sites with suitable and varied environmental characteristics.

Resources

Financing integrated sustainable peatland management should be a long-term policy. Costs of the measures are difficult to calculate with precision, while the cost of not restoring the network of protected raised and blanket bogs can be alternatively considered via proxies, such as the amount of CO_2 emitted. It is critical that the government provide a long-term financial framework to secure the continuity of the sustainable management of shared peatland resources, including both designated (SAC, NHA) and undesignated peatlands. Government bodies should carry out a full economic analysis of these requirements. This would provide a coherent vision of how and why the Irish peatland resource should be managed in an integrated fashion, extending to communities living around the bogs.

Carbon credit schemes could provide financial intervention from additional sources to current EU and state funded projects, as well as a mechanism by which businesses, organisations and individuals could invest in land-management and restoration schemes. It is predicted that carbon offsetting schemes would not only have the potential to deliver significant climate change mitigation, but would also support habitat conservation, provide cleaner water, and generate new sources of income for farmers/ landowners.

Conclusion

This scoping report has focused on integrating and synthesising the scientific information needed to provide recommendations. From the review, four key priority areas have been identified, and within these, solutions have been provided where possible, such as a stakeholder engagement map to further aid with multi-group collaboration, or key actions have been suggested as part of a strategic guidance framework. These recommendations should be implemented to enhance future peatland management in Ireland in order to optimise water quality, while delivering co-benefits for biodiversity and climate change mitigation.

-End of Executive Summary-

Introduction

Peatlands cover an estimated 423 million hectares globally, which equates to approximately 3% of the global land surface Xu et al. (2018). The majority are found in the high latitudes of the northern hemisphere and in the tropics (Figure 1). Climatically, peatlands tend to form in areas where there is an excess of precipitation over evapotranspiration (Moore and Bellamy, 1974). The relatively warm, humid conditions characteristic of maritime regions, such as Ireland, provide more favourable conditions for peat formation than more northern areas (Ovenden, 1990). Furthermore, maritime and oceanic regions are likely to provide a longer growing season and less extreme temperatures than continental areas (Tuhkanen, 1984).

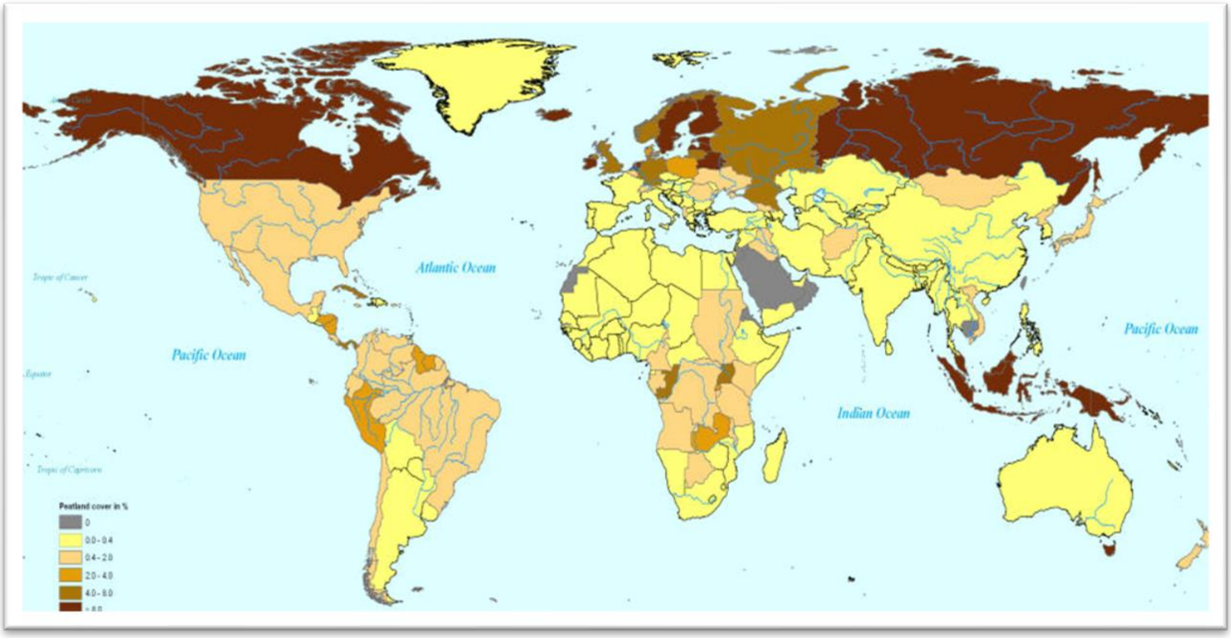


Figure 1: Global peatland distribution. Source: www.wetlands.org

Peat is composed of partially decomposed plant material (Charman, 2002). The quality of the litter and the nutrient status of the peatland strongly determine the rate of decomposition and, therefore, the amount of organic matter that will accumulate as peat. *Sphagnum* litter is particularly important for peat formation, due to the release of phenolic compounds and tannins from the plant tissues resulting in suppressed degradation and organic matter accumulation (Charman, 2002).

The Republic of Ireland (referred to as Ireland henceforth) has one of the largest areas of peat coverage in Europe, at 21% of the total land area (Tanneberger et al., 2017). Irish peatlands are of significant global value. Approximately 50% of blanket bogs considered to be of conservation importance in the European Atlantic Biogeographic Region are found in Ireland (Coll et al., 2014), along with over 50% of the Oceanic raised bog remaining in the EU (Foss and O'Connell, 1998). Here, peatlands can be generally grouped into three broad landscape units (Hammond, 1981): (a) fens, (b) raised bogs, and (c) blanket bogs, although Renou-Wilson (2018) points out that under the Irish classification system (Fossitt, 2000), a fourth group (cutover and cutaway bogs) can also be identified.

Minerotrophic fens, which receive nutrients from groundwater and precipitation, form in places of impeded water movement and typically develop along a gradient from open water to marsh to rich fen, with each vegetation community modifying the hydrological conditions prior to the succeeding community (Muller et al., 2003). This process of terrestrialisation results in a gradual infilling of the water body and can be followed, under suitable climatic conditions, by vertical and lateral growth of the peatland. Further changes in the composition of vegetation takes place as the nutrient status of the peatland is reduced with increasing distance from the groundwater and increased reliance on (low-nutrient) precipitation as a source of nutrients. The transition from fen to bog can occur as a result of external (allogenic) processes, such as climate change or as a result of internal (autogenic) factors. In general, fens demonstrate greater rates of decomposition than bogs as a consequence of lower acidity and higher nutrient status.

As raised bogs only receive nutrients from precipitation, they form in geographical areas where precipitation is greater than evaporation (Charman, 2002). Typically, this has occurred in the Irish Midlands (Figure 2), where peat accumulation commenced in the post-glacial phase, ~ 10,000 years ago (Hammond, 1981). Raised bogs can be up to 14 m deep (average 6–7 m), which has made them attractive for peat extraction (both industrial and domestic) (Renou-Wilson, 2018). Blanket bogs, which also receive nutrients through precipitation, can be divided into Low level Atlantic bogs, which are prevalent along the western seaboard (Figure 2), and High Level Mountain sites, which are found at altitudes greater than 150 m (Hammond, 1981). Blanket bogs are believed to have initiated 4,000 years ago (Renou-Wilson, 2018) and are formed through a process called paludification, whereby peat accumulates directly over former dry mineral soil (Charman, 2002).

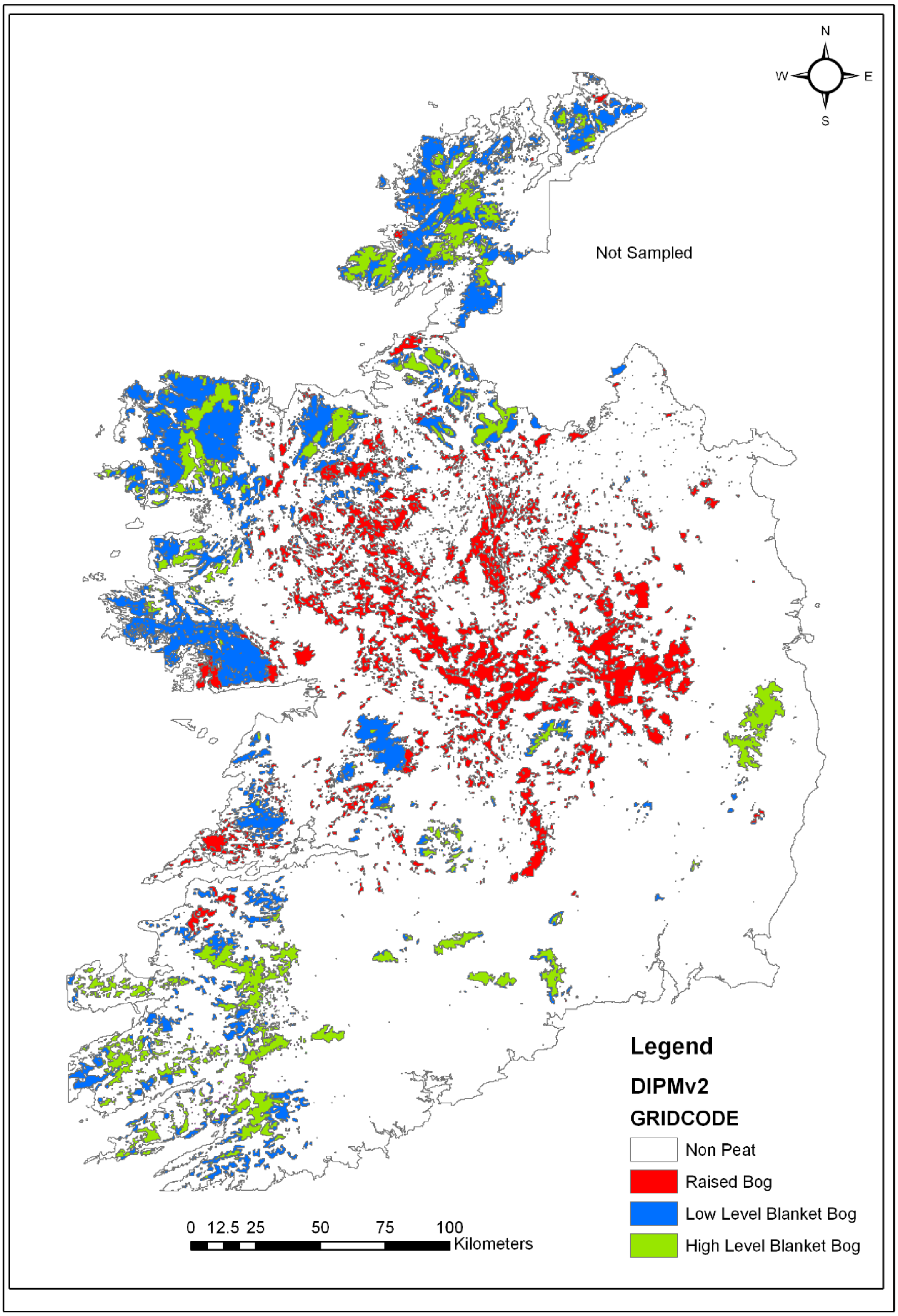


Figure 2: Derived Irish peatland map (Connolly and Holden, 2009). RB = Raised Bog, LLA = Low Level Atlantic, HLM = High Level Mountain.

Hand cutting of peat for domestic fuel use has been a traditional practice for many generations, but this has caused historical and localised damage, resulting in the loss of some smaller bogs in Ireland (Fernandez-Valverde et al., 2006). Cutover bogs are habitats where the peat has been extracted for domestic use. Traditionally, this was carried out manually, but in recent decades the peat is removed with a digger and the peat extruded onto the peatland surface through a hopper. Malone and O'Connell (2009) estimate that up to 612,000 ha of peatlands have been affected by domestic extraction (i.e. turbary). Cutaway peatlands occur in areas where the peat has been extracted industrially, and where it is no longer economically viable to do so. These areas account for approximately 7% of the national peatland area.

With peatlands being such a major component of the Irish landscape, they give rise to important cultural services for rural communities, including spiritual and aesthetic benefits (Feehan et al., 2008), heritage and cultural identity, as well as other uses including providing fuel for energy; forestry; horticultural products; agriculture; and environmental and ecological benefits (Renou-Wilson, 2018) Figure 3.

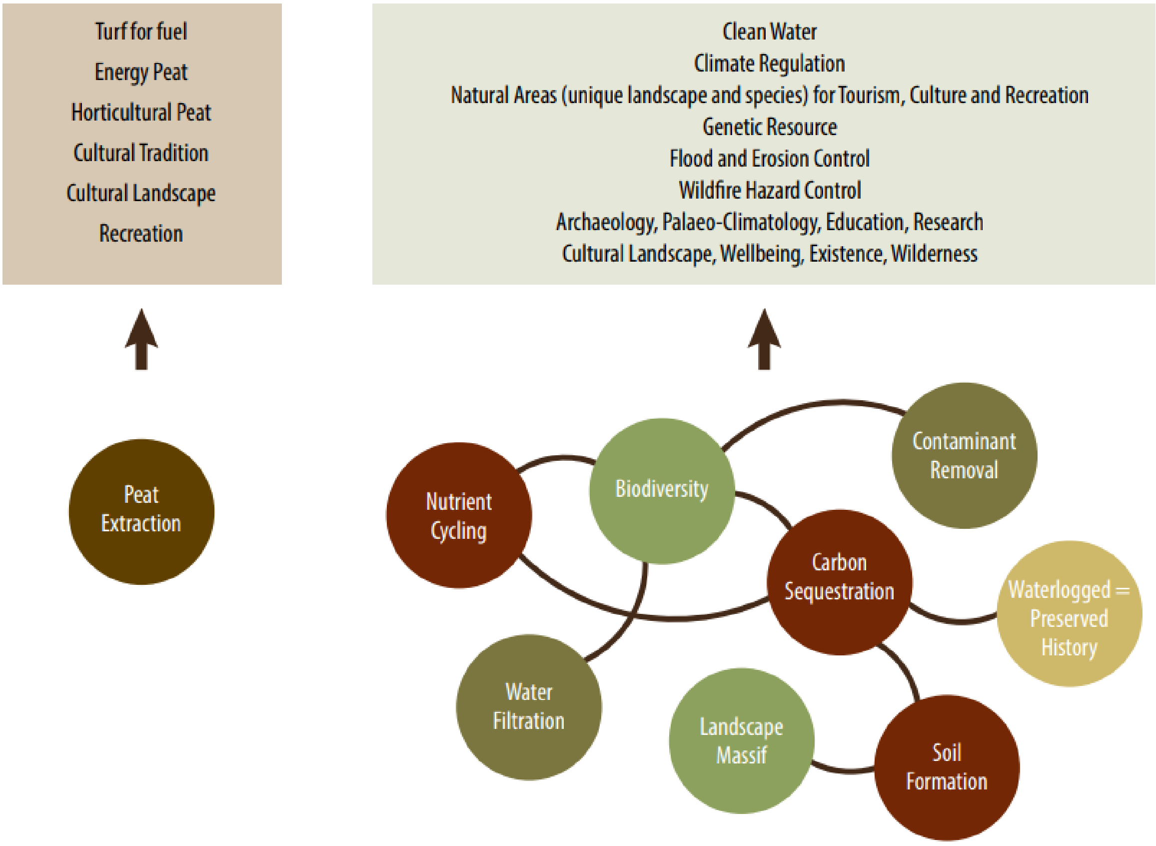


Figure 3: Peatland ecosystem functions and services (NPWS, 2015a).

Despite their value, the majority of Irish peatlands are considered to be degraded to some extent (Douglas et al., 2008). Less than 23% of the original area of fen soils (~ 21,000 ha) in Ireland remain suitable for conservation, while less than 10% of the original area of raised bog is conservation worthy (Malone and O'Connell, 2009). Alongside extraction, other important peat land use categories (both areal and economic) are grassland (on organic soils) and forestry, which cover approximately 420,000 ha (Green, 2020) and 450,940 ha, respectively (Duffy et al., 2020). This has caused widespread damage to peatlands. For example, it is estimated that 72% of the original blanket bog area in Ireland has been lost to overgrazing, peat extraction and afforestation (Malone and O'Connell, 2009). Table 1 summarises the area of peatland under major land use categories.

Table 1: Estimates of area of peatland in Ireland under major land use classifications. Land area references are sourced from Malone and O'Connell (2009)[1], NPWS (2015a)[2], Duffy et al. (2020)[3], Green (2020)[4] and Connolly and Holden (2009)[5].

Land Use Classification	Area (ha)	Percentage of peatland
Near natural (of conservation value)	269,270[1]	18
Domestic cutover	245,259	17
Industrial cutaway	81,000[2]	6
Afforested	450,940[3]	31
Agriculture	420,000[4]	28
Total	1,466,469[5]	100

These land uses require the peatland to be drained resulting in drier conditions and exposure to oxygen, and the resulting microbial activity causes higher rates of peat decomposition and carbon dioxide (CO_2) emissions (Moore and Dalva, 1993). In addition, peatlands also support a range of specialised flora and fauna and niche communities (Minayeva et al., 2017). When degraded, it is not just the peatland specific biota that are affected but also aquatic organisms from the pollutants released. Therefore, healthy and intact peatlands are important for biodiversity on a catchment scale (Ramchunder et al., 2012).

Intact peatlands are beneficial for water quality, as they store atmospherically deposited nitrogen, sulphur, metals, and organic pollutants (Daniels et al., 2008; Rothwell et al., 2010). However, peatland drainage and lowered water tables are associated with water quality impacts, such as surface water acidification (Clark et al., 2005), enhanced leaching of sulphur, nitrate, ammonium, metals, (Daniels et al., 2012, 2008), and dissolved organic carbon (DOC) into drainage water and downstream aquatic ecosystems (Rothwell et al., 2010). Acidification and heavy metal concentrations are known to affect freshwater biota, particularly impacting invertebrate and fish populations (Steinberg and Wright, 1994).

The structure and condition of a peatland also plays an important role in regulating water flow in a catchment. Depending on their location and composition, peatlands can be either a source of flooding or have the potential to reduce floods. Damage to bogs, peat cutting, and associated drainage and loss of vegetation can increase the volume and speed of water leaving the bog, especially on mountain blanket bogs. This rapidly draining water contains higher amounts of DOC and nitrogen due to erosion and leaching of nutrients from the peat (Holden et al., 2004).

Peatlands are also a considerable store of carbon due to the permanently saturated conditions in which they form, resulting in suppressed decomposition of organic matter and therefore an accumulation of carbon, estimated globally at just below 100 Mt C/year (Joosten and Couwenberg, 2008). Whilst peatlands cover just 21% of total land area in Ireland, they hold over 75% of the soil carbon stock (1,566 Mt) (Renou-Wilson et al., 2011). Just ~0.1% of raised bog in Ireland is thought to be actively forming new peat and sequestering carbon (Fernandez et al., 2014), and the amount of unmanaged wetland is still shrinking (Duffy et al., 2020). The few near-natural peatlands remaining are estimated to sequester ~57,402 t C/year, but this is counteracted by emissions from degrading peatlands and associated activities, totalling a loss of ~3 Mt C/year to the atmosphere (Renou-Wilson et al., 2011, Wilson et al., 2013b). It is now thought that activities that include extraction, drainage and cultivation have transformed 90% of the original peat soils in Ireland from carbon sinks to sources (Wilson et al., 2013b).

Impetus for this study

The aim of this scoping study is to provide strategic guidance to An Fóram Uisce (The Irish Water Forum) as to how peatland management can be reimagined in order to optimise water quality improvements while delivering co-benefits for climate change and biodiversity. Peatland degradation has been identified as a common contributory factor in the unfavourable status of many water-dependent habitats and species; and peat extraction is a significant pressure acting on many water bodies. Healthy peatlands help provide natural filtration processes to clean water and reduce the quantity of water entering rivers and lakes; they help regulate the global climate and mitigate climate change; they support unique flora and fauna; and provide multiple cultural services to society. In contrast, degraded peatlands negatively impact water quality, and release ammonium and CO_2 to the atmosphere, sediment and nutrients to water courses, and lead to a reduction in biodiversity.

Five key components will be addressed in the following chapters/Work Packages:

1. Rewetting degraded peatlands
2. Carbon sequestration

3. Social value of peatlands
4. Alternative management options of degraded peatlands
5. Strategic guidance and resources for future integrated management of peatlands

1. Rewetting degraded peatlands

Summary of key messages

- The majority (82%) of peatlands in Ireland are estimated to be drained, and only a small proportion of the remaining natural peatlands have been rewetted and restored.
- Limited extraction sites are known to be rewetted, while the area of rewetted peatlands previously afforested or under agricultural use is unknown. Rewetting has been restricted to areas of conservation value (SAC, NHA).
- Studies show concentrations of nitrogen, phosphorus, base cations, heavy metals, DOC and particulate organic carbon (POC) are increased with drainage, although this depends on site-specific characteristics and management.
- Rewetting has been found to result in long term decreases of inorganic nitrogen, base cations, suspended solids and DOC, as well as increasing biodiversity and carbon sequestration potential.
- In addition, degraded peatlands have been shown to have significantly higher nitrous oxide emissions (a greenhouse gas). Rewetted organic soils have decreased emissions.
- In summary, drainage and removal of surface vegetation alters water chemistry, as well as hydrology and flow regimes, releasing organic material and nutrients, which degrades inland water quality. However, rewetting is an important management technique to improve water quality, reduce greenhouse gas emissions, improve carbon sequestration, and promote biodiversity.
- As the ‘natural’ recolonization of peatland vegetation can take some time following rewetting, restoration techniques (e.g. reseeding or transplanting of essential peatland species) can speed up revegetation and improvements in water quality.

1.1 Overview of peatland drainage and rewetting in Ireland

1.1.1 Historical drainage and land use

The damage to peatlands in Ireland is the result of land use change and peatland utilisation that has occurred over many centuries, but in particular during the last century. There are a number of management activities that degrade these ecosystems, exerting pressures on the functioning underlying services, such as water quality and climate regulation (Evans et al., 2014). Drainage is usually the first step for a number of land-uses, including extraction, forestry, reclamation for agriculture, and more recently for the placement of windfarms (Connolly and Holden, 2017, Renou-

Wilson, 2018). Crucially, according to estimates (Table 1), just 18% of peatland are classed as 'natural' and considered to be of conservation value, whilst 82% are classified under other land uses that require drainage.

Drainage has taken place on Irish peatlands since before the arrival of the Anglo-Normans (12th century) (Kelly, 2000), which highlights the long history of peatland drainage. Population pressures, as well as national famines over the last two centuries, resulted in an intensification of drainage and reclamation of peatlands, particularly fens, for agricultural purposes. In 1808, the Bog Commission was set up in order to map and identify areas that could be drained and brought into agricultural production (Bord na Móna, 2020c). It is thought that peak drainage actually occurred in the 1920s, mostly for domestic peat extraction for fuel, as well as for agricultural uses (Duffy et al., 2020). Since then, various policies have contributed to the historical intensive drainage of peatlands in Ireland, including the Arterial Drainage Act (1945); the Farm Improvement Plan; and the EU Headage grant scheme, which intensified grazing pressures (Renou-Wilson, 2018). As a result, just 3% of fens remain undrained in Ireland (Foss et al., 2001). In recent years, the decline in use of land for agricultural grassland has resulted in many drained peatland areas used for this purpose being abandoned (Duffy et al., 2020). The reduced maintenance of drains has caused some natural rewetting to take place. However, many sites require active drain blocking to aid recovery, and hence remain degraded and likely a source of greenhouse gas emissions (Günther et al., 2020).

A peatland pasture with grazing sheep. Photo: Connie O'Driscoll, Co. Mayo.

A large proportion of raised and blanket bogs are also drained for other purposes. A network of ditches is established to drain peatlands on an industrial scale, for extraction or forestry use for instance. Traditionally, preparation for conversion to forestry involved ploughing to create furrows running down slopes, lowering the water table and increasing runoff times into cross-drains running perpendicular along the edge of the slope (Carling et al., 2001).

An active drain in a Sitka Spruce plantation growing on peat soil.
Photo: Catharine Pschenyckyj.

Pumping systems may be used for preparation for extraction, where water is still in excess, despite a network of drains. Currently, the area of bogs pumped for industrial extraction purposes exceeds extracted bogs without. Following drainage, the removal of the peat during extraction causes further degradation to the physio-chemical and biological elements of the peatland, while the compaction and physical disturbance caused by machinery use during extraction and forestry operations damages structural elements. The cumulative effects from drainage and additional activities with other external pressures, such as climate change, are detrimental to the functioning of the peatland ecosystem and the services provided.

Photo of drains in active (left) and recovering (right) extraction bogs. Photos: David Wilson.

1.1.2 Peatland rewetting in Ireland

In recent years, there has been a move towards more sustainable management of peatlands and restoration of degraded sites has been key to this. Restoration involves restoring abiotic and biotic conditions close to the original state, including the hydrological regime and surface topography followed by the reintroduction of peatland flora, such as *Sphagnum*. Studies have shown that raising the water table to, or near, the surface is sufficient to create suitable conditions to promote recolonization of vegetation, this being crucial to restoration (Tuittila et al., 2000). There has been increasing pressure to rewet sites in Ireland following the publication of the Bogland report in 2011, which recommended that cutaway peatlands be restored where possible (Renou-Wilson et al., 2011). This was later adopted in the National Peatland Strategy (NPWS, 2015a). Then, in 2018 the National Planning Framework stated that the qualities of natural and cultural heritage, including peatlands, should be conserved and enhanced, suggesting restoration should be promoted over rehabilitation only. However, the Climate Action Plan 2019 failed to incorporate this recommendation and instead suggested there should be a development of rehabilitation measures for exploited and degraded peatlands, and to restore/rewet designated sites only (Special Areas of Conservation and Natural Heritage Areas) (DCCAE, 2019).

The area of peatland being used for pasture and forestry that has been rewetted is unknown and is likely to be very low. Rewetting work could take place on some extracted peatlands following the rehabilitation process (where sites are stabilised, so they no longer release pollutants to air and water). Previously, only rehabilitation was required under Environmental Protection Agency (EPA) licencing. As many extracted sites are located close to, or form part of, designated peatland bodies, restoration of extracted sites is crucial to increase the status, area and connectivity between active peat forming habitats in the long term. However, there are a limited number of extraction sites no longer in production that have been rewetted. Bord na Móna have restored 1200 ha of raised bogs to date, with plans to restore a further 1000 ha as part of their Raised Bog Restoration programme (EPA, 2017), although these were sites where mining had not taken place, and where restoration was easier to achieve. In comparison, an estimated 21,000 ha of cutaway/cutover land has been rehabilitated by Bord na Móna (DCCAE, 2019). However, following the announcement of €108 million in funding from the Just Transition Fund, Bord na Móna have now ceased peat extraction for industrial fuel use and have launched the Enhanced Peatland Rehabilitation Scheme, with plans to undertake 'enhanced rehabilitation' or restoration on 33,000 ha (Bord na Móna, 2020a). Unlike previous rehabilitation, whereby drains remained open and vegetation was left to colonise unaided, 'enhanced' rehabilitation involves rewetting through bunding and drain blocking, and other restoration techniques will be included such as *Sphagnum* reintroduction. It should be noted that while Bord na Móna recently announced the cessation of extraction for horticultural products, private companies may well continue.

Rewetting peatlands has been identified as an important management technique to improve water quality, reduce greenhouse gas emissions, improve carbon sequestration, and promote biodiversity (Parish et al., 2008, Bonn et al., 2014). Peatlands can be rewetted by blocking drainage ditches or installing bunds, which raises and stabilises the water table (Gottwald and Seuffert, 2005, Larose et al., 1997, Price, 1997) and increases water retention (Shantz and Price, 2006). This alteration of peatland hydrology is essential for the reestablishment of 'peat building' vegetation such as *Sphagnum,* and for reduced organic matter decomposition, which in turn allows the peatland to revert back to a carbon sink (Chimner and Cooper, 2003). Rewetting peatlands can also contribute to water quality by decreasing the concentration of suspended solids and DOC in the peatland water (Armstrong et al., 2010, Wallage et al., 2006). Rewetting combined with additional restoration measures can improve the biodiversity value of peatlands by providing niche habitats for specialized fauna and flora (Chapman et al., 2003, Minayeva et al., 2017, Parish et al., 2008).

Photo of a site undergoing peatland restoration. Here, a drain has been blocked with pear dams and the water table is at the peat surface. Photo: David Wilson.

The peatland restoration scene is still in its infancy in Ireland. Individual raised bogs have been restored either through (1) rewetting of drained only bogs that Bord na Móna had not extracted ; (2) drain blocking and removal of failed crops from afforested sites owned by Coillte under EU LIFE programme; (3) restoration efforts in conjunctions with communities and NGOs (Irish Peatland Conservation Council) as well as a side product of other nature conservation programme aiming to protect the Hen Harrier ((http://www.henharrierproject.ie/) or the Freshwater Pear Mussel ((https://www.pearlmusselproject.ie/). Recently, the Living Bog project (EU LIFE programme) has been a major driver of restoration work for designated raised bogs, with 12 SAC sites (2,600 ha) being restored (The Living Bog, 2016). This however represents only 7% of the SAC network of designated raised bogs. The Wild Atlantic Nature LIFE IP programme the LIFE-IP PAF Wild Atlantic Nature programme (2021-2028) is the next significant piece of restoration concentrating on Ireland's blanket bog NATURA Network along the Atlantic seaboard. Wild Western Peatlands project will also the restoration and/or rehabilitation of approximately 2,100 hectares of Atlantic blanket bog that is currently planted with commercial spruce and pine forests (https://www.coillte.ie/coillte-nature/ourprojects/wildwesternpeatlands/).

When restoring these degraded peatlands to reinstate the services they provide, it is important to understand the current impacts of drainage and future impacts of rewetting. Therefore, this work package will review our understanding of the impacts of drainage and rewetting peatlands on water quality and other services, such as biodiversity, at different spatial and temporal scales.

1.2 Impacts of drainage and rewetting

1.2.1 Water quality

Peatlands typically contain more than 95% water in a natural, undrained state (Charman, 2002). Water from peatlands moves directly into lakes via streams and rivers, as well as into groundwater reserves, transporting nutrients and organic matter, and influencing the chemical properties and biota of aquatic ecosystems. Drainage and removal of surface vegetation alters the peat and pore water chemistry, as well as hydrology and flow regimes, equating to degradation of inland water quality. Crucially, drainage causes oxygenation of the peat and enhanced microbial decomposition, releasing organic material and nutrients. Also, ombrotrophic (nutrient-poor) peat generally has low concentrations of nitrogen (N), phosphorus (P) and potassium (K), and so fertilisers are sometimes applied for afforestation and agricultural uses (Beltman et al., 1996, Renou et al., 2000), which may also be transported throughout the landscape or further stimulate microbial activities and release of nutrients and organic material. The type and quantity of material leaching from degraded peatlands and entering streams varies depending on site specific characteristics and management activities, but typically concentrations of N, P, DOC and particulate organic carbon (POC) are increased (Armstrong et al., 2010, Holden et al., 2004, Kløve et al., 2010). Significant changes in water quality in response to drainage, which have been noted by studies in Ireland, are summarised in Table 2, and these are discussed below in the context of international studies also.

Table 2: A summary of key changes in water chemistry associated with peatland management activities related to extraction or forestry.

Reference	Water chemistry	Peatland management
AQUAFOR Project- (Allott et al., 1997, Kelly-Quinn et al., 1997, Tierney et al., 1998)	Reduced macroinvertebrate abundance and/or loss of acid-sensitive taxa with increasing catchment forest cover.	Drainage, fertilisation and afforestation
Feeley et al. (2013)	Dissolved organic carbon and inorganic aluminium concentrations were higher in forested catchments. The primary driver of acidity was strong organic anions, which generally increased with increasing forest cover.	Drainage, fertilisation and afforestation
HYDROFOR Project (Kelly-Quinn et al., 2016)	Lakes within forested catchments had elevated concentrations of phosphorus, nitrogen, dissolved organic carbon (DOC), aluminium, manganese and iron, with the highest concentrations of each recorded from lakes with	Drainage, fertilisation, clearfelling and afforestation

	forest clearfelling compared with the lakes in unplanted blanket bog. The chydorid communities of the lakes in the forested catchments, especially clearfell lakes, were associated with elevated DOC, iron, aluminium, TP, total nitrogen (TN), ammonia, SRP and chlorophyll a concentrations.	
SANIFAC Project (Rodgers et al., 2010)	P concentrations at a downstream station rose to levels two orders of magnitude greater than baseline and took 4 years to return to pre-clearfelling levels in a forested peat catchment.	Coniferous forest on upland peat
Jennings et al. (2009)	Coniferous forest on upland peat leads to: -Increased particulate P export -Over double the amount of sediment loss compared to undisturbed upland peat.	Coniferous forest on upland peat
Cummins and Farrell (2003a), Cummins and Farrell (2003b)	Clearfelling resulted in large increases in molybdate-reactive phosphorus (MRP), increases in calcium and alkalinity, ammonium, nitrate, potassium, magnesium, DOC, aluminium. MRP also increased with fertilisation.	Drainage, clearfelling, fertilisation, reforesting
Renou-Wilson et al. (2011)	Ammonium concentrations greater than natural/near natural peatlands.	Drainage and extraction
Renou-Wilson and Farrell (2007)	Slightly higher P concentrations compared to reported values for intact sites.	Drainage, fertilisation, and afforestation on cutaway
Barry et al. (2016a)	DOC export of 12–48 g C m^{-2} yr^{-1}, which is higher than natural/near natural peatland sites (Section 2.1.3; Table 5).	Drainage, pasture

In addition, drainage impacts on peatland hydrology by lowering the water table and altering the flow regime, including increases in infiltration rates and baseflows, and reduced saturation-excess overland flow (Robinson, 1985, Tiemeyer et al., 2007). Throughflow is increased due structural changes from greater oxidation, such as the formation of pipes and macropores (Holden et al., 2006). As a result, hydraulic conductivity and flow to inland waters is increased making pollutants more mobile.

Studies on the impacts of rewetting peatlands in Ireland have generally focused on greenhouse gas dynamics, and there is limited work on the effects on water quality. Studies elsewhere have found rewetting results in reduced concentrations of various pollutants, including inorganic N, base cations and DOC (Lundin et al., 2017, Menberu et al., 2017). Increases in ammonium and P have been observed for rewetted sites and more work is needed to understand the long-term temporal changes in these trends. Further pollution control methods may be needed at sites where this occurs. In the long-term, by re-establishing the unique abiotic conditions of peatland ecosystems, the structural and functional processes are reinstated, including the imbalance between primary production and decomposition (Minayeva et al., 2017).

Restoration is also associated with increased biodiversity, not just on site but also throughout the catchment by improving the quality of aquatic ecosystems (Ramchunder et al., 2012). In summary, rewetting has been found to result in short term increases, but long term decreases, in inorganic N, base cations and DOC. Typically, concentrations are below or quickly become lower than concentrations from drained sites. There is limited work on heavy metal release following rewetting but concentrations are likely to follow the same trend.

1.2.2 Nitrogen cycle and water quality

In an undamaged peatland system where oxygen-poor processes dominate, ammonium and nitrate - the products of oxygen dependent processes - are typically low in concentrations (Rydin and Jeglum, 2013). However, these are known to increase with lowered water tables and other damaging activities, such as peat extraction (Schouten, 2002), as increased oxygen availability creates a beneficial environment for oxygen-dependent microbial activity, including mineralisation and nitrification. Microbial processes, which may increase with drainage and rewetting in relation to N cycling, are summarised in Figure 4.

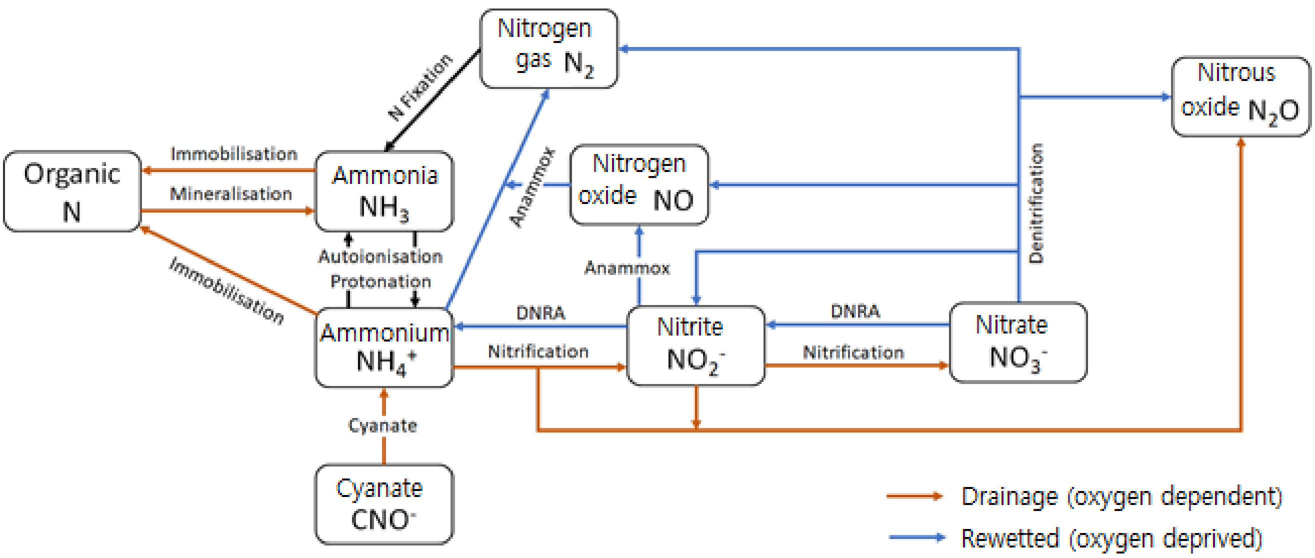


Figure 4: An overview of the processes and interactions in the nitrogen (N) cycle. Processes and N pathways in orange are oxygen dependent and so likely to increase with drainage and other degrading peatland management, whilst oxygen deprived processes, which are likely to increase with rewetting and restoration, are in blue. DNRA refers to Dissimilatory nitrate reduction to ammonium.

Mineralisation of organic matter is enhanced by drainage and an increase in oxygen supply, which produces ammonia, that may also be transformed into ammonium. In addition, cyanate (a recently recognised process in the N cycle) may also increase with greater oxygen supply producing more ammonium (Palatinszky et al., 2015, Stein, 2015). However, there is limited understanding of this process in organic soils, including its relative contribution to ammonium concentrations or how it may be impacted by peatland management.

Nitrification may also increase in drained peat, due to elevated levels of ammonium (from mineralisation) and oxygen (as this is an oxygen-dependent process). This is a step wise process which produces nitrite through ammonium oxidation, which is then further oxidised to nitrate. As nitrate consumption (denitrification, an oxygen deprived process) is lower in drained peat, nitrate can accumulate (Russow et al., 2013). Furthermore, N deposition may prime microbial communities and further increase mineralisation of organic material and release of nutrients for drained peatlands (Currey et al., 2010).

Increases in ammonium following drainage are thought to be short term (Moore, 1987), but are known to remain high for peatlands in production for extraction (Andersen et al., 2011, Heikkinen et al., 2018, Kløve, 2000) or following clearfelling (Cummins and Farrell, 2003a). In Ireland, concentrations greater than the 0.065 mg/l threshold have been observed downstream of extraction sites, meaning the water body would fall short of Good Ecological Status (Department of Housing, 2018). One ad-hoc study of an industrial cutaway peatland in Ireland found high concentrations of ammonium and ammonia compared to values reported for intact sites (Renou-Wilson et al., 2011). Elevated N levels have also been measured in water draining peat extraction sites in Finland (Kløve, 2001). In addition, the channels of drainage networks provide shorter pathways between peatland N sources and streams, and limited opportunity for dilution and denitrification.

Drinking water abstracted from surface water and groundwater sources that contain high levels of nitrate represent a public health risk and the Drinking Water Regulations (2014) set a 50 mg/l parametric value for nitrate and 0.5 mg/l of nitrite. Ammonium monitoring is required as an indicator parameter for pollution events and the parametric value is 0.30 ug/l. When reaching water systems, the excess N can have serious impacts on aquatic ecosystems. Ammonia remains un-ionised in waters greater than pH 7.2 units, and this form is toxic to fish in low concentrations, with toxicity increasing with temperature (Camargo and Alonso, 2006). Ammonium may be further converted to nitrate downstream (Daniels et al., 2012), removing the dissolved oxygen from water that is essential for the survival of aquatic life (Camargo and Alonso, 2006). Nitrate has been shown to occur in low flow summer conditions when supply of nutrients is lower and denitrification rates are higher (Maberly et al., 2002), leading to eutrophication of oligotrophic (nutrient poor) waters. In addition, nitrite is also toxic to aquatic biota.

In contrast, rewetted peatlands can be associated with greater ammonium concentrations due to increased DNRA (dissimilatory nitrate reduction to ammonium) activity (Lundin et al., 2017, Jahangir et al., 2020). Ammonium production may also vary with depth. Regina et al. (1999) found increased ammonium concentrations when raising the water table of peat from a drained fen in a monolith experiment, with greater concentrations at depths -12 to -35cm, and lower concentrations at the surface. In addition, rewetting results in reduced nitrification, increased denitrification, as well as enhanced plant coverage and nutrient uptake which decreases nitrate (Lundin et al., 2017). Therefore, while there may be some elevated levels of ammonium for rewetted peatlands compared to natural sites, this is typically lower than drained and degraded peatlands, and release of nitrate is reduced. However, the nutrient status of the peat is a key factor in determining N release. For instance, Koskinen et al. (2017) found elevated N exports following drain blocking in forested Finnish peatlands were greater in nutrient rich peatlands, such as those in mesotrophic (intermediate nutrient level) catchments.

1.2.3 Phosphorus release

High organic matter content and the resulting limited availability of sorption (movement of a compound from solution to a solid stage) sites causes low P sorption capacity in peat and hence increased mobility in solution (Daly et al., 2001). As with N, drainage increases oxygen availability, which catalyses mineralisation of organically-bound P (Holden et al., 2004). For instance, one study in North Carolina found 28 times more P compared to run off from an undrained site (Richardson, 1983). Concentrations have only been slightly larger for Irish cutaway peat (33 µg/l) (Renou-Wilson and Farrell, 2007) compared to intact peatland waters rarely exceeding 20 µg/l (Schouten, 2002, Kenttämies, 1981). However, data from Ireland is limited. Phosphorus is generally accepted as the limiting nutrient in inland freshwaters (Smith et al., 1997), and orthophosphate values >30 µg/l for rivers and >20 µg/l for lakes can lead to eutrophication (Lucey et al., 1999). High P concentrations have been measured in waters from drained peatlands (Moorkens, 2006). Some protected species (freshwater pearl mussel) and habitats (oligotrophic lakes) require much less than this (<10 µg/l TP) (Moorkens, 2006).

Increased P release from drained peatlands is typically associated with forestry activities, initially at the afforestation phase, then again at the clearfelling stage and additionally at the reforestation phase if second rotation fertilisation is warranted. Blanket peat has low P adsorption capacity, low hydraulic conductivity and P is easily mobilised to runoff following application. As the stand begins to establish and the prepared site experiences natural regeneration, the P is taken up by the plants. This cycle is disrupted following clearfelling creating an increased labile (unbound) P pool in harvested areas, which is again easily mobilised to runoff. Rodgers et al. (2010) demonstrated that it takes four years after clearfelling for P in the receiving water to return to baseline concentrations, and O'Driscoll et al. (2011) demonstrated that this coincides with regrowth of natural vegetation and uptake of P on a site. P peaks are associated with storm events whereby the drained peat site quickly transports P to the receiving watercourses.

Restoring peatlands have been shown to increase P exports, at least In the short term. For instance, Koskinen et al. (2017) found drain blocking in a nutrient-rich forested peatland increased exports of P, as well as DOC and N. Rewetting the nutrient rich topsoil, such as with restoration of agricultural peatlands, can result in P becoming mobile and causing algal blooms and eutrophication of water bodies (Harpenslager et al., 2015). However, long-term rewetting over a period of 30 years is reported to lock P into organic matter, and to transform labile P to stable P fractions at the surface horizons of the different peatland types (Negassa et al., 2020).

1.2.4 Acidity changes

While naturally occurring, organic acids contribute significantly to water acidity in peatland catchments, this can be exacerbated by drainage associated with afforestation, as drying of the soil can increase oxidation of organic matter and generate carboxylate anions. Forest growth and associated increases in nutrient and base cations uptake from the soil, in addition to increased evapotranspiration, results in concentrated chemicals in throughfall. Preferential flow is further enhanced by increased root growth, leading to faster transport of pollutants to streams. High precipitation events associated with blanket peat areas contribute to increased rates of runoff, reducing contact between acidic drainage and acid neutralising bases and leading to acidic episodes in streams.

Acidity has a direct impact on ecology and drinking water chemistry. The parametric value for drinking water is between 6.5 and 9.5 pH units and pH control is a critical component of water treatment and distribution with a direct influence on coagulation, disinfection and plumbosolvency. Remineralisation is necessary in some water sources where pH is too low. From an ecological perspective, acidification is associated with the elimination of many plant and invertebrate taxa and the loss of salmonid fisheries. When buffering capacity is exhausted soils act as a source of both acids and metals for receiving water. Therefore, acidity is associated with high concentrations of monomeric aluminium, H^+ and other metals such as iron and manganese and lower concentrations of calcium and magnesium. However, DOC has been shown to improve toxicity associated with aluminium by binding together.

1.2.5 Heavy metal release

The cation exchange capacity of peat means that it also contains some heavy metals (including lead, manganese, zinc and mercury), and when drained, the adsorbed metals become mobile and may reach water systems (Winkler and DeWitt, 1985). Heavy metals are usually toxic to aquatic organisms and can bioaccumulate. A review of studies on Canadian peatlands found limited data on heavy metals draining peat, but manganese and aluminium tended to be more prevalent in concentrations (Andersen et al., 2011). For forested peatlands, large amounts of iron and aluminium have been shown to be released after clearfelling and following forest drainage (Palviainen et al., 2004, Cummins and Farrell, 2003a, Joensuu et al., 2002). Likely sources of heavy metals and major ions in forested peatlands are inorganic fertilisers applied at the start of the forest cycle, decay of the humus layer and accumulated needle litter layer, and leachate from felled trees (Drinan et al., 2013). The speciation, toxicity, bioavailability and ultimate fate of metals is controlled by the complexation between heavy metals and DOC (Bidoglio and Stumm, 2013). High concentrations of aluminium in acidic waters have been shown to be toxic to fish (Driscoll et al., 1980).

Increased concentrations of iron have been found following rewetting, from <1 mg dm^{-3} to >60 mg dm^{-3} (Fenner et al., 2001). There is limited research available on the short and longer term effects of rewetting on metals. Studies have shown that maximum accumulation rates of anthropogenically derived elements peaked pre-1970s in Ireland (Coggins et al., 2006). It is probable that drainage has somewhat depleted these reserves and with reductions in atmospheric pollutants the 'source' component of heavy metals as a contaminant may be somewhat reduced. It is likely where heavy metal concentrations are higher they will respond in a similar way to DOC and P with short term increases followed by a longer-term decrease (Nieminen et al., 2020, Kaila et al., 2016).

1.2.6 DOC and water quality

DOC is also naturally released from peatlands into streams. However, drainage and associated peatland utilisation often results in a greater DOC release to nearby water bodies, which impacts on carbon dynamics and water quality. An analysis of available datasets suggests a 60% increase in DOC flux with peatland drainage (Evans et al., 2016b). While DOC is itself not toxic it can transport contaminants and toxic compounds; it is a precursor for trihalomethanes, it influences the solubility, mobility and thus bioavailability of toxic metals such as mercury, copper and lead, and can bind organic pollutants (Ledesma et al., 2012). Increases in DOC concentrations associated with managed peatlands can adversely affect treatability of raw water by interfering with process operation and increasing costs via chemicals, energy and sludge waste management.

Rewetting can cause increases in pore water DOC and colour, for water draining peatlands in the months and first few years following the raised water table (Fenner et al., 2001, Hughes et al., 1998, Worrall et al., 2007a). Höll et al. (2009) found significantly lowered DOC concentrations for a site rewetted 20 years previously compared to a drained site. Such studies suggest there may be initial increases in DOC following rewetting, but this is lower in the long term due to store exhaustion and flushing processes, and lowered decomposition rates for organic matter (Wallage et al., 2006, Höll et al., 2009).

Water draining an extracted peatland. The dark brown colour indicates high levels of DOC.
Photo: Florence Renou-Wilson.

Carbon dynamics associated with degraded, rewetted and intact peatlands, including DOC, are discussed in detail in Chapter 2.

1.2.7 Suspended solids

Degraded peatlands are particularly vulnerable to gully formation and the deposition of large amounts of sediment into streams, due to reduced moisture content with drainage and removal of peatland vegetation with extraction, forestry and agriculture activities. The low density of peat means erosion can occur easily, particularly with surface desiccation (Foulds and Warburton, 2007a, Foulds and Warburton, 2007b). Gullies form at desiccation cracks and other points of weakness, which accelerates erosion and the loss of POC impacting on carbon budgets (Evans and Lindsay, 2010). In addition, entire blocks of peat can be transferred to streams due to mass failure when surface flows undercut peat banks (Evans and Warburton, 2001). Streams in catchments with active drains have been found to contain higher suspended solid, finer bed sediment and fine particulate organic matter concentrations, than streams in catchments with blocked drained or intact peatlands (Ramchunder et al., 2012).

Increased concentrations of suspended sediment associated with peat extraction and forestry activities affect the treatability of raw drinking water leading to challenges with process optimisation. Increased sediment loads can also affect aquatic ecosystems downstream. Increased turbidity and reduced light penetration results in lowered primary production (Parkhill and Gulliver, 2002). Also, increased sediment loads have been shown to smother aquatic primary producers, and reduce the prevalence of filter feeding organisms by blocking feeding mechanisms (Broekhuizen et al., 2001).

1.2.8 Nitrous oxide emissions

Although not widely studied, typically intact peatlands have very low emissions of nitrous oxide (a greenhouse gas) (Regina et al., 1996, Martikainen et al., 1993, Leppelt et al., 2014, Wilson et al., 2016a), while peatlands with recent and historical drainage may become nitrous oxide sources (Regina et al., 1999, Regina et al., 1996). Changes in water table levels with drainage alters oxygen availability at depth, as well as the surface peat temperature, all of which influences microbial communities and functioning (Mäkiranta et al., 2009). The sensitivity of nitrifiers and denitrifiers to oxygen availability means that soil moisture and oxygen concentrations are key factors for controlling nitrous oxide fluxes in peat (Rubol et al., 2012, Firestone and Davidson, 1989). Intact peatlands have relatively stable water tables which remain near the surface (Holden et al., 2011), resulting in permanent saturation and release of nitrogen gas due to low levels of nitrification and complete denitrification taking place. In contrast, water table levels have been shown to fluctuated for both drained and restored peatlands (Holden et al., 2011). The periodic saturated conditions and fluctuations in the water level promote increases in nitrous oxide emissions (Rubol et al., 2012, Freeman et al., 1992, Kandel et al., 2019).

Croplands and grasslands on organic soils have significantly higher nitrous oxide fluxes (0.98 ± 1.08 and 0.58 ± 1.03 g nitrous oxide-N m^{-2} a^{-1} respectively) than natural peatlands (0.07 ± 0.27 g nitrous oxide-N m^{-2} a^{-1}) (Leppelt et al., 2014). Studies have shown peat extraction and cultivation sites are similarly sources of nitrous oxide (Järveoja et al., 2016, Salm et al., 2012), during both summer and winter seasons (Mustamo et al., 2016). Forested peatlands have also been shown to be nitrous oxide sources (Ojanen et al., 2010). In a study examining different management activities on afforested peatland, the highest cumulative nitrous oxide release was observed in the standing forest (1173 ± 422 g N ha^{-1} yr^{-1}) while the lowest release was observed from the intact peat site (15 ± 193 g N ha^{-1} yr^{-1}) (Finnegan et al., 2012). Clearfelling the forest caused a decrease in average nitrous oxide flux (from

1.7 to 0.7 g N ha^{-1} d^{-1}) while the regenerated buffer had the lowest values at 0.6 ± 0.42 g N ha^{-1} d^{-1}, attributed to a rise in the water table. A clear need has been identified for further quantitative evidence on nitrous oxide on afforested peatlands (Vanguelova et al., 2018).

Vegetation is also an important variable in controlling emissions. Unrestored bare peat has been shown to have greater nitrous oxide emissions than restored sites with vegetation cover (Järveoja et al., 2016). Vascular species in particular can moderate emissions. Cotton grass (*Eriophorum vaginatum)* has been shown to increase uptake of nitrate, reducing its availability for denitrification and hence nitrous oxide production (Brummell et al., 2017, Silvan et al., 2005). Other studies have found small nitrous oxide fluxes with little contribution to total greenhouse gas budgets for peatlands, regardless of bare peat status or vegetation cover (Jordan et al., 2016).

The peat nutrient status (and, therefore, the N availability for microbial processing) also impacts on nitrous oxide fluxes. Ombrotrophic peatlands have very low to negligible emissions, while minerotrophic (nutrient rich) fens have greater nitrous oxide emissions that are more susceptible to increases in water table fluctuations (Martikainen et al., 1993, Regina et al., 1996, Juszczak and Augustin, 2013). As 77% of Ireland's fens have been lost to agriculture and reclamation (Malone and O'Connell, 2009), it is likely there has been a significant and long term release of nitrous oxide from these sites. However, there have been limited studies on emissions of nitrous oxide in Ireland, especially for reclaimed fenlands. One study comparing drained organic grasslands in Ireland found the nutrient rich site was a small source of nitrous oxide (0.16 g N m−2 yr^{-1}), while the nutrient poor site was not (Renou-Wilson et al., 2014).

There is very little work on the effects of rewetting on nitrous oxide emissions. A study comparing a rewetted and drained industrial cutaway peatland in Ireland found there were no nitrous oxide emissions at either site (Wilson et al., 2016c). However, rewetted organic soils are predicted to have decreased N_2O emissions (Wilson et al., 2016a).

1.2.9 Drainage and rewetting impacts on biodiversity

As peatland vegetation communities include specialised species suited to higher water tables, drainage results in a loss of these species. Drainage damages biodiversity at all scales (from nano to landscape), which impedes ecosystem functioning and the services provided (Minayeva et al., 2017). A variety of species within the peatland are affected, including birds (Väisänen and Rauhala, 1983), amphibians (Mazerolle, 2003), mesofauna (invertebrates 0.1–2mm in size) (which have been found to increase, likely due to more favourable conditions for decomposition) (Silvan et al., 2000) and microorganisms (responsible for biogeochemical cycling) (Reumer et al., 2018).

The effects of drainage and rewetting on plant communities have been more widely studied. *Sphagnum*, which is known as a 'peat building' species and is essential to the functioning of active peatlands, is reduced in diversity and abundance, or is eliminated with drainage. Studies have shown that raising the water table to, or near, the surface is sufficient to create suitable conditions to promote recolonization of peatland vegetation (Tuittila et al., 2000). However, the level of degradation and the proximity to intact sites determines the speed of vegetation recovery when rewetting and restoring. Farrell and Doyle (2003) found that raising the water table enabled recolonization and spread of *Sphagnum* for an Atlantic cutaway blanket bog, but this was more efficient when remnants of the original bog and, therefore, a source of propagules remained within the production area. The 'natural' recolonization of peatland vegetation can take some time, and it may be 50–100 years before indicators show the habitat has reached good quality and 'active' status (Mackin et al., 2017). Vacuum-mined peatlands are known to have a much slower recovery time compared to block-cut sites (Lavoie et al., 2003). One study in Ireland found the vegetation in a restored domestic cutover site in Ireland to be similar to non-degraded bogs, whilst the rewetting of an industrial bog did not result in the natural bog flora community (Renou-Wilson et al., 2019). Therefore, for severely degraded peatlands, restoration may involve the reseeding or transplanting of essential peatland species following rewetting, including the reintroduction of bryophytes.

Recovering vegetation on a cutaway bog. Calluna (heather) has established alongside a number of trees. Photo: Florence Renou-Wilson.

As peatlands and terrestrial aquatic ecosystems are intrinsically linked, degradation of peatlands can cause deterioration of habitats and reduced biodiversity throughout the catchment. However, there are limited studies on the impacts of drainage and other peatland management activities on nearby stream ecology (Ramchunder et al., 2009). Macroinvertebrate communities are altered in catchment streams where peatland drainage takes place, likely due to the higher concentrations of suspended sediment and fine particulate organic matter. Ramchunder et al. (2012) found drained sites had a lower abundance of Ephemeroptera, Plecoptera and Trichoptera larvae, and a higher abundance of Diptera larvae when compared to drain blocked sites (which had similar communities to intact sites). A loss of these species lower down in the food chain has a knock-on effect on species higher up who depend on these organisms. Crucially, rewetting and associated revegetation improve water quality, such as reduced DOC concentrations reaching waters, and improves uptake of nutrients, which reduces the occurrence of algal blooms in nearby open waters (Higgins, 2006, Qassim et al., 2014).

Overall, rewetting is associated with increased biodiversity, not just on-site for peatland specific species, but also throughout the catchment, by improving the quality of aquatic ecosystems

(Ramchunder et al., 2012). Restoration efforts can also be designed to create more diverse conditions and microhabitats to promote biodiversity, such as bog pools (Beadle et al., 2015).

2 Carbon cycling in intact, degraded and rewetted peatlands

Summary of key messages

- Peatlands play a vital role in regulating the global climate by acting as long-term carbon sinks.
- Natural peatlands have a high water and reduced decomposition rates, leading to an accumulation of dead plant material and organic matter, and the carbon contained therein.
- Drainage, however, has a fundamental impact on the carbon that is stored in the peat Figure 6and the peatland invariably switches from acting as a long-term CO_2 sink to a large CO_2 source, as well as releasing more waterborne carbon (DOC).
- DOC concentrations in water courses have been increasing across Northern Europe since the 1980s, with research suggesting greater increases from catchments with drained peatlands, and yet there is little data on DOC concentrations in Irish surface waters.
- Rewetting has been shown to reduce CO_2 emissions and DOC concentrations, although methane emissions may increase.
- Peatlands are likely to be severely affected by climate change, including changes in decomposition rates leading to a loss of the carbon stored; increased fire risk; and reduced peatland area. Degraded peatlands are expected to be more vulnerable to climatic changes.

2.1 Overview of carbon dynamics in peatlands

Natural peatlands have played a vital role in regulating the global climate over the last 10,000 years (Frolking and Roulet, 2007) by acting as long-term carbon sinks (Nilsson et al., 2008, Rinne et al., 2020, Koehler et al., 2011), whereby the amount of carbon dioxide (CO_2) fixed by the peatland vegetation during photosynthesis is greater than that released during (a) respiration by the plants and the microbial communities, (b) methane (CH_4) emissions, (c) leaching and surface runoff of DOC, (d) losses of POC, and (e) dissolved inorganic carbon (DIC). Conversely, the influence of climate on the initiation and development of peatland ecosystems is well established (see Introduction) (Yu et al., 2010, Glebov et al., 2002).

Global peatlands are estimated to store over 600 billion tonnes of carbon (Yu, 2012, Page et al., 2011), while peatlands in Ireland contain between 1–1.5 billion tonnes (Tomlinson, 2005, Eaton et al., 2008, Cruickshank et al., 1998). Estimates of the peat carbon store is derived from three factors: peat depth, bulk density (i.e. density of the peat), and carbon content. However, precise estimates are constrained to a large degree by uncertainty over the depth of peat sites globally (particularly in remote areas), and by the inherent variability in bulk density values and peat carbon content both *between* and *within* peatland sites. For instance, ongoing research in Ireland (https://www.ucd.ie/auger/) has shown that the variability in bulk density values and carbon content can be considerable from the upper to the lower peat layers, but also between land use categories (i.e. near-natural, peat extraction, grassland and forestry). Moreover, "new" global peat deposits are continually being discovered (e.g. https://congopeat.net/), which would further indicate that current estimates of the global peatland carbon store may be off by a substantial margin (see also Nichols and Peteet, 2019).

Peat coring with a Russian auger to determine bulk density values Photo: David Wilson.

2.1.1 Carbon dioxide (CO_2)

Peatland plants "fix" CO_2 from the atmosphere during photosynthesis and release a considerable portion back to the atmosphere during respiration[1] (known as autotrophic respiration). Some of the fixed CO_2 is used to form the basis of new plant tissues but over time, plant litter and root exudates are deposited into the peat where they are oxidised within the acrotelm (the oxygen rich layer above the water table) and CO_2 is released back to the atmosphere from microbial respiration (known as heterotrophic respiration) (Figure 5). The amount released to the atmosphere can vary considerably depending on the depth of the acrotelm, which in turn is determined by the position of the water table (Nedwell and Watson, 1995).

[1] Respiration is the process by which living things break down glucose molecules to release energy, requiring oxygen, and produces carbon dioxide.

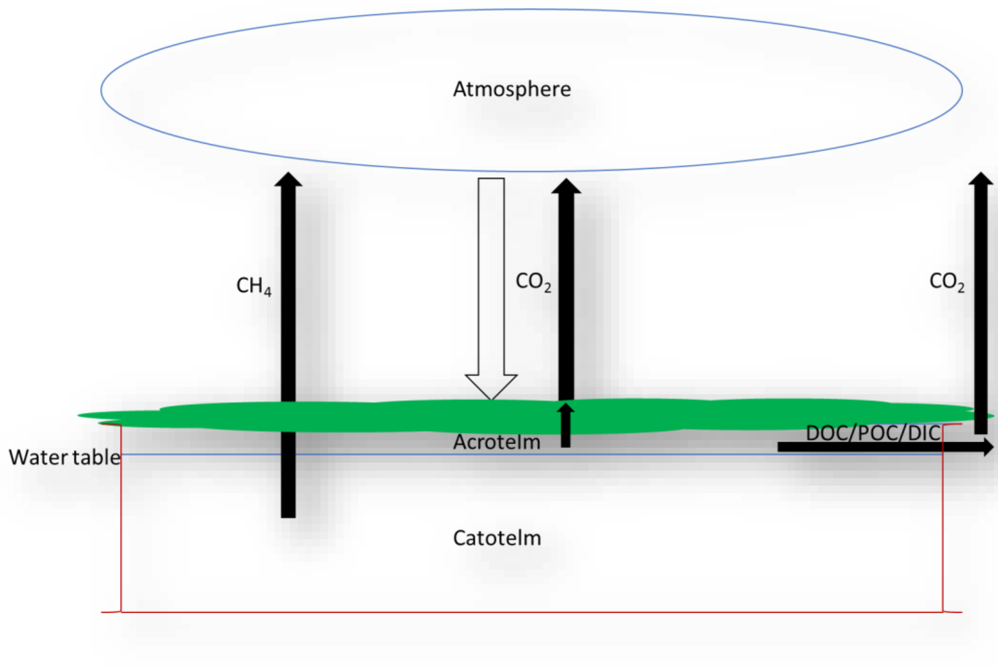


Figure 5: Simplified schematic of carbon dynamics in a natural peatland. Thickness of the arrow indicates the relative strength of the flux. Acrotelm denotes the relatively oxygen-rich layer above the water table, and catotelm denotes the oxygen-poor layer below.

Around 10% of the plant material produced (and the carbon contained therein) will be deposited below the water table into the oxygen-poor catotelm (Clymo, 1984, Francez et al., 2000) where the rate of decomposition occurs at a much slower rate than decomposition at the surface (Clymo et al., 1998). Over time, the organic matter content (and the carbon contained therein) accumulates and the peatland grows vertically and horizontally (Clymo, 1984).

Transparent chamber used to measure CO_2 fluxes at Clara, Co. Offaly.
Photo: David Wilson.

Carbon dioxide (CO_2) fluxes are strongly influenced by a range of abiotic and biotic factors that are themselves subject to variation. For example, photosynthesis is driven by light and by the growth stage of the vegetation, and maximum seasonal photosynthesis occurs in mid-summer with maximum annual irradiation and plant biomass (Alm et al., 1997, Wilson et al., 2007). Respiration in peatlands has been shown to be strongly controlled by temperature, in particular, at or near the peat surface (Renou-Wilson et al., 2019, Alm et al., 1997) and by the moisture status of the peat (water table depth is often used as a proxy for soil moisture/oxygen content). The relationship between respiration and the position of the water table has been well established in field studies (Alm et al., 1997, Silvola et al., 1996). In general, a lowering of the water table increases the depth of the oxygen-rich zone and promotes increased oxygen-dependent respiration and subsequent CO_2 losses to the atmosphere.

2.1.2 Methane (CH_4)

Wetlands account for around 20% of total global methane emissions (Saunois et al., 2020), and natural or near-natural peatlands are a significant source of atmospheric methane (see Table 3). Methanogenesis (i.e. CH_4 production) is a microbial process that requires the complete absence of oxygen (Svensson and Sundh, 1993). The bacteria responsible for methane production belong to the domain Archaea (Galand et al., 2002) but depend on other oxygen-deprived bacteria for the degradation of the complex organic material released by plants (Joabsson et al., 1999) with several groups of microbes necessary for the degradation of organic matter to methane (Svensson and Sundh, 1993).

Methane production is strongly influenced by environmental factors. The close relationship between methane fluxes and the position of the water table have been reported by numerous studies (e.g. Bubier et al., 1993, Huttunen, 2003). In general, a decrease in methane emissions is associated with a deeper water table (Saarnio et al., 1997). The position of the water table is central in influencing potential methane production and oxidation rates, as it determines both the moisture and oxygen concentrations within the soil (Kettunen, 2003). Spatial variation of methane fluxes in peatlands have been widely reported at both the landscape and microscale (Saarnio et al., 1997, Strack et al., 2004, Laine et al., 2007). Similarly, fluxes can also vary diurnally (Yavitt and Knapp, 1995, Käki et al., 2001), seasonally (Saarnio et al., 2007, Laine et al., 2007) and interannually (Shurpali and Verma, 1998, Bubier et al., 2005).

Dark chambers used to measure CH4 fluxes at Moyarwood, Co. Galway. Photo: David Wilson.

2.1.3 Waterborne carbon

Carbon is exported fluvially (i.e. waterborne) from peatlands in several forms, which can be divided into organic and inorganic forms, or dissolved and particulate fractions (Barry et al., 2016a). Dissolved organic carbon (DOC) is commonly the most considerable component, and is naturally released from peatlands into streams (Drösler et al., 2014). It results from the breakdown of plant material and is primarily composed of organic acids (e.g. fulvic or humic acids) (Charman, 2002). DOC accumulates in the pore waters, with the majority of DOC produced in the upper peat layers, and is flushed out by water movement (Charman, 2002). High concentrations of more humic, high molecular weight DOC in peatland streams and water courses are very noticeable, indicated by the brown colour of the water. DOC can be returned to the atmosphere[2] as CO_2 (or methane), or transferred to lake sediments or long-term carbon stores, such as the deep ocean or marine sediments (Müller et al., 2015).

V-notched weir and instrumentation to measure dissolved organic carbon (DOC). Photo: Mark O'Connor.

Particulate organic carbon (POC) is considered to be a negligible component of waterborne carbon in natural sites (Drösler et al., 2014), although one study of Irish peatland pasture sites found POC equated to ~10% of the field scale flux (Barry et al., 2016a), compared to 6.5% for a near-natural Atlantic blanket bog (Koehler et al., 2011). Losses can become very large when bare peat surfaces are exposed to fluvial and wind erosion (Evans et al., 2016a). Compared to DOC, a greater proportion of POC may be translocated from the peatland to other stable carbon stores, such as freshwater or marine sediments (where it will not lead to CO_2 emissions) (Wilson et al., 2016a). Nonetheless, Evans et al. (2016a) estimate that over half of the POC exported from a peatland could eventually be converted to CO_2. Waterborne carbon fluxes from organic soils, which comprise bicarbonate ions, carbonate ions and free CO_2, are collectively termed dissolved inorganic carbon (DIC) (Drösler et al., 2014). DIC fluxes are generally negligible in waters draining from bog peat due to the low solubility of CO_2 at low pH levels, but can be substantial in fen peats (Evans et al., 2016a).

2.2 Near-natural peatland carbon fluxes in Ireland and United Kingdom

To date, only one near-natural peatland site in Ireland has been monitored for CO_2, DOC and methane (Table 3). This site, located in a blanket bog at Glencar, Co. Kerry, has been found to be an annual CO_2 sink (56 g C/m^2/yr) but an annual source of DOC (14 g C/m^2/yr) and methane (4.1 g C/m^2/yr) (Table 3). While the values for Glencar are similar to other near-natural sites in the United Kingdom (see Table 3), the CO_2 value is greater than the Tier 1 emission factor derived by the Inter-Governmental Panel on Climate Change (IPCC) for greenhouse gas (GHG) inventory reporting (Blain et al., 2014), and

[2] Although data is limited, the majority of the exported DOC (~ 90%) is converted to CO_2 through photo- and/or biodegradation in rivers, standing waters and oceans (Evans et al., 2016a).

lower than the Tier 1 DOC and CH_4 emission factors (Table 3). DIC and POC data in near-natural peatlands in Ireland and the UK remain scarce (Table 3).

Table 3: Annual carbon dioxide (CO_2), methane (CH_4), dissolved organic carbon (DOC), dissolved inorganic carbon (DIC), and particulate organic matter (POC) balances (g C/m^2/yr) from natural and near-natural peatland sites in Ireland and United Kingdom. For comparison purposes, derived Tier 1 emission factors (Blain et al. 2014)) are shown for nutrient poor peatlands in the temperate zone. Negative values indicate carbon uptake (removals) by the peatland, and positive values indicate carbon losses (emissions) from the peatland.

Site	Country	Peatland type	CO_2	CH_4	DOC	DIC	POC	Reference
			g C/m2/yr	g C/m2/yr	g C/m2/yr	g C/m2/yr	g C/m2/yr	
Glencar	Ireland	Blanket bog	-56	4.1	14			Koehler et al. 2011, McVeigh et al. 2014
Forsinard	Scotland	Blanket bog	-114	4.3	10.3			Levy and Gray 2015
Forsinard	Scotland	Blanket bog			22.4	0.6	2	Gaffney et al. 2020
Auchencorth Moss	Scotland	Blanket bog	-64	0.3	18.3	12 to 16		Dinsmore et al. 2010,2013, Helfter et al. 2015
Brocky burn	Scotland	Blanket bog			19			Dawson et al. 2004
Conwy	Wales	Blanket bog	-136	4.5	19			CEH. Unpublished data.
Moor House	England	Blanket bog			5.8			Gibson et al. 2009
Moor House	England	Blanket bog			23			Billet et al. 2010
Widdybank Fell	England	Blanket bog			9.8			Gibson et al. 2009
Temperate Zone		Nutrient poor	-23	9.2	24			Blain et al. (2014)

2.3 Carbon dynamics in degraded sites

The effects of land use change on carbon dynamics are summarised in Table 4. The vast majority of peatlands in Ireland have been impacted to some extent by farming, peat extraction or forestry (Wilson et al., 2013a). Key to all these activities is drainage of the peat to facilitate the movement of farm machinery and livestock, the extraction of peat, and economic tree growth. Drainage, however, has a fundamental impact on the carbon that is stored in the peat Figure 6 and the peatland invariably switches from acting as a long-term (small) CO_2 sink to a large CO_2 source (cf. Table 4 & Table 5).

Work by Evans et al. (2016a) suggests that DOC losses increase by around 60% following drainage. Indeed, drainage and associated peatland utilisation often result in a greater DOC release to nearby water bodies, due to to erosion and leaching from decomposing peat (Armstrong et al., 2010, Holden et al., 2004, Wallage et al., 2006). This impacts on water quality, which has implications for the water treatment industry, i.e. increased coagulant costs, increased sludge costs, and fouling of network (Ritson et al., 2016, Jennings et al., 2006). In addition, lack of, or inadequate removal of DOC by water treatment (such as slow sand filters, coagulation-flocculation-clarification and others) followed by disinfection can produce harmful by-products, such as total trihalomethanes (TTHM), with peatland areas being associated with exceedances of TTHM (O'Driscoll et al., 2018b). TTHM's are carcinogenic compounds that increase the risk of disease if inhaled or ingested (WHO, 2005). Drained and cutover peatlands have been shown to export more DOC than restored and natural peatland sites (cf. Table 5 & Table 6), and lead to discoloration of nearby water bodies (Armstrong et al., 2010). In contrast, methane emissions have been found to decease considerably following peatland drainage (cf. Table 4

& Table 5) as the peat profile becomes less oxygen-poor (and methane is converted to CO_2). However, drainage ditches may still function as methane hotspots in the wider peatland landscape (Peacock et al., 2017).

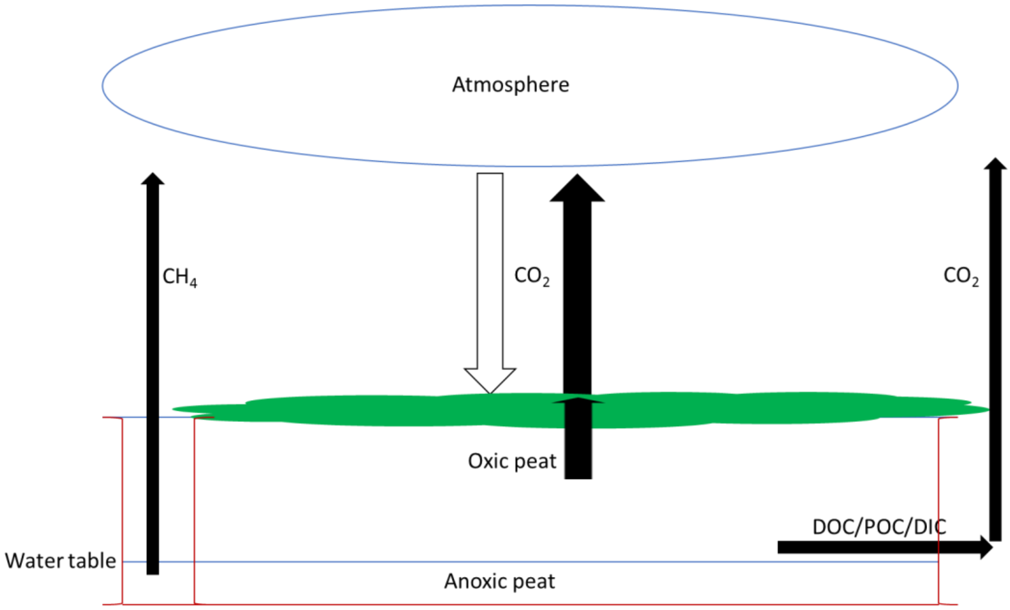


Figure 6: Simplified schematic of carbon dynamics in a drained peatland. CO_2 = carbon dioxide, CH_4 = methane, DOC = dissolved organic carbon, POC = Particulate organic carbon, DIC = dissolved organic carbon. Thickness of the arrow indicates the relative strength of the flux. Oxygen-rich peat denotes the relatively oxygen-rich layer above the water table, and oxygen-poor peat denotes the oxygen-poor layer below the water table.

Degraded peatlands are less resilient and more sensitive to environmental change, including recovery from acidification, rising temperatures and drought (Page and Baird, 2016, Renou-Wilson and Wilson, 2018, Harris et al., 2020). Importantly, DOC concentrations have been increasing in acid sensitive areas of the Northern Hemisphere over the last few decades due to recovery from acid deposition (Pschenyckyj et al., 2020, Evans et al., 2006, Monteith et al., 2007). As soil pH increases, DOC becomes more soluble and mobile. It is also thought that N deposition, which has remained high, may have raised the 'acid recovery DOC baseline' to above pre-industrial levels (Sawicka et al., 2017), and may continue to contribute to increasing DOC trends after pH has stabilised through enhanced plant productivity (Rowe et al., 2014).

Table 4: Effect of land use change on carbon emissions from Irish peatlands.

↑ = small increase, ↑↑ = moderate increase, ↑↑↑ = large increase, ↓ = small decrease, ↓↓ = moderate decrease, ↓↓↓ = large decrease, ?? = unclear.					
Land use		**Change in C emissions**			
From	**To**	**Management action**	**CO_2**	**CH_4**	**DOC**
Near-natural[1,2]	Industrial peat extraction[3]	Total vegetation removal Intensive drainage Removal of peat	↑↑↑	↓↓	↑
	Domestic peat extraction[3,4]	Partial vegetation removal Indirect drainage Partial removal of peat	↑↑↑	↓↓	↑
	Grassland[5]	New vegetation cover Drainage Fertilisation	↑↑↑	↓↓	↑
	Forestry[6]	New vegetation cover Drainage Fertilisation	??	↓↓	↑
Drained[7]	Restored[7,8]	Drain blocking Rise in water level Plant introduction (possible)	↓↓↓ or ↑↑	↑↑	↓
[1]McVeigh et al. (2014), [2]Koehler et al. (2011), [3]Wilson et al. (2015), [4]Regan et al. (2020), [5]Renou-Wilson et al. (2014), [6]Drösler et al. (2014), [7]Wilson et al. (2016c), [8]Rigney et al. (2018).					

In Ireland, most carbon studies have been undertaken in degraded sites, which is not altogether surprising given that 82% of the peatlands in the country are classed as degraded. All degraded Irish sites that have been monitored have been shown to be CO_2 sources but are at the lower range of the IPCC Tier 1 values (Table 5). Methane emissions have also been found to decrease substantially (in comparison to natural sites), while DOC, POC and DIC studies in these peatland types are relatively rare. A model based on the UK shows that the increasing DOC trend is greater for drained catchments, with a predicted 15–30% increase over 10 years compared to a 3% increase for an near-natural peatland catchment (Worrall et al., 2007b). Despite decreasing sulphur deposition (EPA, 2020b) and observations of increased water colour in Ireland (Sepp et al., 2018), there has been limited long-term monitoring of trends in DOC concentration. The International Cooperative Waters Programme found there was a significant increase in DOC for three lakes in Ireland between 1990 and 2001 (Skjelkvåle et al., 2005). Another long-term study in Ireland found a significant increase in DOC concentrations in peat and peaty podzol soil waters, which were associated with declining acidity (Johnson et al., 2013). Forestry has also been associated with episodic acidity events unrelated to declining acid deposition, but caused by greater strong organic anions with increased forest cover (Feeley et al., 2013).

Table 5: Annual carbon dioxide (CO2), methane (CH4), dissolved organic carbon (DOC), dissolved inorganic carbon (DIC), and particulate organic matter (POC) balances (g C/m2/yr) from degraded peatland sites in Ireland and United Kingdom. For comparison purposes, derived Tier 1 emission factors (Drösler et al., 2014) are shown for nutrient poor and nutrient rich peatlands in the temperate zone. Negative values indicate carbon uptake (removals) by the peatland, and positive values indicate carbon losses (emissions) from the peatland.

Site	**Country**	**Land use**	**CO_2**	**CH_4**	**DOC**	**DIC**	**POC**	**References**
			g C/m2/yr	g C/m2/yr	g C/m2/yr	g C/m2/yr	g C/m2/yr	
Moyarwood	Ireland	Cutover	141.1	0.5				Wilson et al. In prep.
Blackwater	Ireland	Cutaway	151	0				Renou-Wilson et al. 2019
Glenvar	Ireland	Grassland	85 to-99	0 to 1.49	6 to 19	20 to 24.4	2 to 6.4	Renou-Wilson et al. 2014 Barry et al. 2016
Lanesboro	Ireland	Grassland	233	0	37.7	44.7	7.9	Renou-Wilson et al. 2014 Barry et al. 2016
Boora	Ireland	Cutaway	182					Wilson et al. 2015
Turraun	Ireland	Cutaway	286					Wilson et al. 2015
Abbeyleix	Ireland	Cutover	16 to 219	2.7 to 8	10.4	1.1 to 1.5		Regan et al. 2020
Glenlahan	Ireland	Cutover	203					Wilson et al. 2015
Clara	Ireland	Cutover	176					Wilson et al. 2015
Clara	Ireland	Cutover	108 to 151	1.1	6.4 to 15.4	0.34 to 0.66		Regan et al. 2020
Bellacorick	Ireland	Cutover	42 to 138	0				Wilson et al 2016
Middlemuir Moss	Scotland	Cutover	93					Wilson et al. 2015
Forsinard	Scotland	Forestry			20.3	0.3	0.7	Gaffney et al. 2020
Little Woolden	England	Cutaway	170					Wilson et al. 2015
Bakers fen	England	Fen Grassland	319	13.7				Peacock et al. 2017
Rosedene	England	Fen cropland	393	20.4				Peacock et al. 2017
Fenns, Whixall & Bettisfield	England	Cutover	-65	1.46				Creevy et al. 2019
Hexhamshire Common	England	Drained	-18	1.6				Rowson et al. 2010
Temperate		Nutrient poor	260 to 530	0.18 to 0.61	31			Drösler et al. (2014)
Temperate		Nutrient rich	360 to 610	0.25 to 3.9	31			Drösler et al. (2014)

2.4 Carbon dynamics in rewetted/restored sites

Rewetting offers the potential to reduce CO_2 emissions (through raising of the water table close to the surface of the peat) (Strack et al., 2014, Wilson et al., 2016a) and, in some cases, return the CO_2 sequestration function characteristic of natural peatlands (Renou-Wilson et al., 2019, Swenson et al., 2019, Nugent et al., 2018, Wilson et al., 2016c). At the same time, methane emissions are likely to increase following rewetting (Renou-Wilson et al., 2019, Günther et al., 2020, Wilson et al., 2016c), and it is unclear as to how long emissions will remain elevated until the ecosystem reaches levels comparable to natural sites (Wilson et al. 2016a). Moreover, although the magnitude of change in carbon movement following rewetting is likely to vary considerably between peatland sites (Wilson et al., 2016a). Evans et al. (2016a) suggest that the increase in DOC losses following drainage may be reversed in the longer term through re-wetting, although variability between studies may be substantial. In the long term, rewetting peatlands and restoring them to a more natural state can result in decline of DOC alongside other pollutants (Anderson and Ross, 2011; Armstrong et al., 2010; Wallage et al., 2006), with important improvements for aquatic biodiversity, downstream fisheries, and human health.

Table 6: Annual carbon dioxide (CO2), methane (CH4), dissolved organic carbon (DOC), dissolved inorganic carbon (DIC), and particulate organic matter (POC) balances (g C/m2/yr) from rewetted/restored peatland sites in Ireland and United Kingdom. For comparison purposes, derived Tier 1 emission factors (Blain et al., 2014) (Blain et al., 2014) are shown for nutrient poor and nutrient rich peatlands in the temperate zone. Negative values indicate carbon uptake (removals) by the peatland, and positive values indicate carbon losses (emissions) from the peatland.

Site	Country	Land use	CO_2	CH_4	DOC	DIC	POC	References
			g C/m2/yr	g C/m2/yr	g C/m2/yr	g C/m2/yr	g C/m2/yr	
Bellacorick	Ireland	Rewetted cutaway	-104	9				Wilson et al. 2016
Moyarwood	Ireland	Rewetted cutover	-104	19.3				Wilson et al. In prep.
Blackwater	Ireland	Rewetted cutaway	66	5				Renou-Wilson et al. 2019
Glenvar	Ireland	Rewetted grassland	85 to -40					Renou-Wilson et al. 2016
Pollagoona	Ireland	Rewetted forestry	131.6	2.94				Rigney et al. 2018
Scohaboy	Ireland	Rewetted forestry	585	4.8				Rigney et al. 2018
Abbeyleix	Ireland	Rewetted cutover	3 to -92	6 to 14.2	10.4	1.1 to 1.5		Regan et al. 2020
Clara	Ireland	Rewetted cutover	2 to -51	6 to 10.6	6.4 to 15.4	0.34 to 0.66		Regan et al. 2020
Forsinard	Scotland	Rewetted forestry			22.4	0.27	1	Gaffney et al. 2020
Lonielist	Scotland	Restored forestry	80					Hambley et al. 2019
Talaheel	Scotland	Restored forestry	-71					Hambley et al. 2019
Fenns, Whixall & Bettisfield	England	Rewetted forestry	-42 to -64	2.5 to 5				Creevy et al. 2019
Cow Green	England	Rewetted blanket bog			8.2			Gibson et al. 2009
Hexham	England	Rewetted blanket bog			9.7			Gibson et al. 2009
Temperate Zone		Nutrient poor	-23	9.2	24			Blain et al. 2014
Temperate Zone		Nutrient rich	50	21.6	24			Blain et al. 2014

2.5 Peatland functioning and climate change

There is clear evidence that the global climate has warmed considerably over the last 50 years, driven by increases in the atmospheric concentration of greenhouse gases, such as CO_2 and methane (IPCC, 2018). Moreover, computer model projections indicate that over the next century, global temperatures are on track to increase by between 1.5 and 4.5 °C, weather patterns will change regionally (e.g. changes in frequency and distribution of rainfall), and sea levels will rise (IPCC, 2013). In Ireland, climate change projections indicate that by the end of the current century, air temperatures will be much higher across all seasons, and that summers will become much drier, while the other seasons will be much wetter (Fealy et al., 2018).

Peatlands are likely to be severely affected by climate change (Table 7). For instance, short term, interannual climatic variations have been shown to significantly affect the rate of peat and carbon accumulation in natural peatlands as carbon dynamics are particularly sensitive to periods of drought (Alm et al., 1999, Carroll and Crill, 1997), the magnitude of temperature and precipitation variation within the growing season (Waddington and Roulet, 2000), and the timing and frequency of precipitation events (Griffis and Rouse, 2001). Increased temperatures will promote decomposition of the peat and release further CO_2 to the atmosphere, especially if temperature increases occur in combination with prolonged drought periods. A modelling study by Jones et al. (2006) has suggested that the predicted changes in climate are likely to result in a severe diminution of the Irish peatland cover by 2075. A more recent modelling study by Ferretto et al. (2019) has projected that more than

50% of the carbon currently stored in Scottish blanket bogs (which exist under the same climate regime as Ireland) could be lost by 2050.

Other Irish studies (Coll et al., 2016, Coll et al., 2014) have suggested that climate change impacts will depend on peatland type (lowland peatlands to be more affected than upland ones) and geographical location (southern regions more at risk). Under climate change scenarios, a long-term decline in the distribution of actively growing blanket peat is projected to occur, especially under high-emissions scenarios (Clark et al., 2010). Moreover, degraded peatlands are expected to be more vulnerable to climatic changes, with drained agricultural peat soils, especially, projected to become even larger hotspots of CO_2 emissions (Renou-Wilson and Wilson, 2018).

Table 7: Projected impacts on Irish peatlands and associated mitigation and adaptation options (Renou-Wilson and Wilson, 2018).

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[e]
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[j]

Rising air and soil temperatures will also increase fire activity in Irish peatlands, promoting the ignition of fires that will release large amounts of greenhouse gases and a plethora of other pollutants (Wilson et al., 2015). Moreover, the indirect effects of climate change in peatlands (e.g. change in plant species composition) could be more important for litter decomposition (and fire fuel loading) than the direct effects of climate change from increased temperatures and decreased rainfall (Bell et al., 2018). Increased summer droughts, driven by climate change, are likely to put *Calluna* heathlands and the carbon stores contained therein, at greater risk than bogs and fens (Grau-Andrés et al., 2018). Future climate conditions are projected to drive a reduction in the heathland distribution (Coll et al., 2016).

Crucially, the rising temperatures associated with climate change is thought to enhance peatland decomposition and DOC release to inland waters (Dieleman et al., 2016, Worrall and Burt, 2005). Koehler et al (2009) found that DOC concentration in streams were strongly influenced by seasonal changes in temperature, based on one year of continuous monitoring at Glencar blanket bog in Co. Kerry, Ireland. Moreover, a model focused on two peatland catchments in Ireland predicted substantial increases in future DOC concentrations at both sites under future climate change scenarios (Jennings et al., 2006). However, increases in DOC due to raised temperatures may be offset by reductions in precipitation and river flow in Ireland (outside of extreme precipitation events) (O'Driscoll et al., 2018a).

3 Cultural Ecosystem Services and Social Values of Peatlands

Summary of key messages

- Cultural ecosystem services are an important category of benefits that people gain from natural environments, such as peatlands, and should be considered in policy and decision making alongside other ecosystem services at national, regional, and local scales.
- The assessment and valuation of cultural services requires engaging with a range of stakeholders, including local communities, land managers, interest groups, state agencies, local authorities, and all potential users of these services, through participatory processes that enable expression of a broad range of values.
- Articulation of social and cultural values for decision making involves deliberative and qualitative methods, as many cultural services are not governed by market values and thus cannot be measured using monetary metrics.
- Cultural ecosystem services are diverse and complex because of the social relationships and values that underpin them. An integrated, pluralistic approach creates a foundation for inclusive and ethical ecosystem service valuations that bridge biophysical, socio-cultural, economic, health, and local or indigenous perspectives on values and valuation.
- Currently in Ireland, there is a shift in cultural values and societal norms around the uses and value of peatlands, from economic and utilitarian values, to an appreciation of the cultural aspects peatlands provide. These shifts in values from unsustainable use of peat to management for biodiversity and ecosystem services, are largely positive and supportive of sustainable peatland management.

3.1 Overview of cultural ecosystem services concepts and debates

3.1.1 Approaches to classifying cultural ecosystem services

The concept of cultural ecosystem services (CES) provides a means to identify and assess the cultural aspects of an ecosystem's contribution to human wellbeing so they can be included in policy and decision-making alongside provisioning and regulating ecosystem services (ES) (Fish et al., 2016). The aim is to render more visible the complexity and variety of ways in which humanity depends on nature. Yet various conceptual and practical challenges exist due to the complex relationships and pathways between ecosystems and human wellbeing, especially relating to assessing and measuring cultural services and values. CES have traditionally been defined as the nonmaterial benefits people obtain from ecosystems through spiritual enrichment, cognitive development, cultural heritage, reflection, recreation, and aesthetic experiences, all of which contribute to human health and well-being (Sarukhán et al., 2005). However, cultural services can also provide material benefits, such as income from recreation businesses, provisions from foraging for wild food, or turf cutting linked to social arrangements, such as turbary, all of which have cultural significance (Byg et al., 2017, Waylen et al., 2016). It has also been argued that nearly all ecosystem services are influenced by culture in some measure (Hirons et al., 2016).

Several different systems for classifying and assessing CES have been developed, including the Millennium Ecosystem Assessment (MA), the Economics of Ecosystems and Biodiversity (TEEB), the Common International Classification of Ecosystem Services (CICES), the IPBES system of Nature's Contributions to People (NCP), and the UK National Ecosystem Assessment (UKNEA) (Appendix 2). These approaches aim to support ES categorisation and comparison, and different systems are used in different contexts depending on the aims and objectives of valuation or assessment. Figure 7 outlines the evolution of the concept of CES from being viewed as a non-material, linear flow of benefits from nature to people towards more relational, place-based approaches, which integrate different types of knowledge, both disciplinary as well as local and indigenous knowledge. More recent developments, such as the Life Framework of Values demonstrate an increasing focus on values over services, emphasizing interconnectedness, and incorporating place and intrinsic values, as well as values relating to the non-human world (Kenter, 2019). This focus encourages a move away from decision-making that primarily values the environment in an anthropocentric sense to incorporate the perspectives of diverse human communities, as well as "the wider community of life"[3] (Earth Council, 2000).

[3] This term from the Earth Charter (2000) is used to denote humanity's co-existence and interconnectedness with other species.

Figure 7: Systems for classifying cultural ecosystem services and general value orientation[4]. Source: Appendix 2.

Cultural ecosystem services can be defined as the environmental settings, locations or situations that give rise to changes in the physical or mental states of people, where the character of those settings is dependent on living processes; they can involve individual species, habitats and whole ecosystems (Haines-Young and Potschin, 2018). In this definition, the biophysical setting (or the 'service' that gives rise to the benefits) is distinguished from the spiritual, recreational, aesthetic and other outcomes or benefits. This approach was developed in the UKNEA in order to facilitate measurement of CES, given that biophysical features of the environment, and the activities undertaken there are easier to measure than the less tangible benefits (Fish et al., 2016). Cultural services frequently depend and interact with provisioning, regulating and supporting services of ecosystems.

Thus, CES reflect the interaction between environmental settings and cultural practices that together form goods and services that generate benefits for human well-being (Bryce et al., 2016). These practices often reflect cultural values held by people about the environment and are the mechanism through which cultural benefits arise from their biophysical and cultural contexts. Cultural practices at peatland sites can relate to traditional use of peatlands for fuel, recreational activities, citizen science projects, protection of cultural heritage, and creative and artistic responses to ecosystems (Figure 8). This conceptualisation of CES is place-based, relational and non-linear, rather than depicting

[4] Value orientation is intended as a guide only. In reality, value dimensions are interconnected and many of the classification systems attempt to reflect value pluralism

a unidirectional flow of benefits from nature to people (Fish et al., 2016). In this context, CES is "about understanding modalities of living that people participate in, that constitute and reflect the values and histories people share, the material and symbolic practices they engage in, and the places they inhabit" (Fish et al, 2016, p.210). The relationship between nature and people is perceived as collaborative, with CES understood as co-produced by people and the environment (Fish et al., 2016). Benefits can be described as the goods and experiences that are valued and are the level at which people can most easily relate ecosystems to themselves. Services relate to the ecosystem processes underpinning benefits and are the level at which ecosystem dynamics might be considered in planning and management, while values are the preferences, principles and virtues that we hold as individuals or groups (Chan et al., 2012).

While there remains a lack of clarity on how to measure cultural ecosystem services and social values, this ever-evolving field of theory and practice provides a useful way to examine wider social-ecological debates about how we value and manage the natural environment. It is unlikely that common standardized approaches to CES categorization and valuation will materialize due to the many disciplines and interpretations of culture that exist, however, different approaches can be employed to suit different contexts (Hirons et al., 2016).

3.1.2 Why are cultural ecosystem services important?

It is now widely accepted that understanding human dimensions of environmental issues improves conservation and management outcomes, rather than depending on biophysical knowledge alone (Bennett et al., 2017). Such insights can be applied to minimize conflict between stakeholders; design communication strategies to appeal to people's different values; and understand perceptions of different management decisions (Ives and Kendal, 2014). CES offers a way to incorporate cultural and social values into discussions around sustainable land use, integrated management of catchments, and sustainable management of ecosystems. As demand for cultural services continues to grow in both rural and urban areas (Milcu et al., 2013), the capacity of many ecosystems to continue providing cultural benefits may decrease, unless carefully managed to minimise impacts (Waylen et al., 2016). Thus, understanding demand for CES can inform objective setting in management and enable better consideration of trade-offs (Milcu et al., 2013).

Figure 8: Demand for cultural services of peatlands is increasing as they provide important opportunities for recreation, education, research, and inspiration. Photos: Kate Flood.

Consideration of cultural services and associated cultural and social values can also raise awareness of an ecosystem's value, promoting dialogue between stakeholders and local communities, and informing the design policy of instruments that are fair and equitable (Milcu et al., 2013). Insights into the importance of CES at local levels can enable better consideration of trade-offs and "trigger the evolution of the ecosystem services framework in a direction that more deeply engages people and accounts for social values" (Milcu et al, 2013, p.10).

Despite their importance, CES are often over-looked in decision-making due to the challenges associated with assessing and valuing them (Dickinson and Hobbs, 2017). The past decade of scholarship has highlighted the need to improve integration of CES into ecosystem service valuations and assessments to ensure these dimensions of ecosystems are accounted for (Milcu et al., 2013). Yet there persists a tendency to focus on easily measured CES, such as recreation and ecotourism, which has the effect of "further deepening the gap between counting that which matters to people and that which is easy to measure" (Milcu et al, 2013, p.7). However, the inclusion of a full range of cultural services is vital to balance the emphasis on monetary valuation and ensure equity and fairness (Hirons et al., 2016, Bullock and Flood, 2020).

3.1.3 Challenges for describing the value of cultural ecosystem services

There are various challenges for CES research and valuation in representing the complex pathways and relationships between ecosystems and human wellbeing, and the intersection of values involved in these relationships (Hirons et al., 2016) (Table 8). These include the intangible and incommensurable nature of many CES, and ethical or sacred values that defy monetary valuation, or are incompatible with a concept of nature as providing services (Chan et al., 2012). Moreover, it can be challenging to differentiate specific ecological characteristics of species or ecosystems that give rise to cultural services and their associated benefits (Parker et al., 2016). Generally, people respond to whole landscapes, which are made up of a mosaic of habitats, topographies, and abiotic features rather than a specific ecosystem or species, and many cultural services are interconnected (Waylen et al., 2016). Despite these challenges, methods for valuing and assessing CES have been developed over the past decade which include quantitative and qualitative approaches, monetary and non-monetary valuation, methods which emphasise social learning between stakeholders, and deliberative and non-deliberative processes, as summarised by Hirons et al (2016, p.559).

A defining feature of CES is their reliance on social factors, in that all cultural services involve human inputs and perception, which can be influenced by individual and societal attitudes and beliefs, and the values which underpin these. Other inputs might include built capital (boardwalks to provide access for recreation); human capital (an educator or other specialist leading a guided walk); and social capital (communities getting together to help conserve their local landscape), although co-production of CES is generally said to relate to perception of the environment in the mind of the user rather than monetary or labour inputs (Dickinson and Hobbs, 2017). Another defining feature of CES is their incommensurability, which is when there is no common measurement or standard of comparison between two different services (Dickinson and Hobbs, 2017). Given the range of values that underpin CES, trade-offs between different ES become difficult when "values cannot be reduced to a single metric such as price" (Bullock, 2017). Alternatively, the idea of value pluralism recognises the multiplicity of values that must be taken into account when managing and conserving ecosystems (Hirons et al., 2016, Díaz et al., 2020).

Table 8: Characteristics of CES which make them challenging to assess and value. Source: Milcu et al. (2013), Dickinson and Hobbs (2017), Kenter (2019) and Waylen et al. (2016).

Characteristics	Challenges
Lack of common terminology & consistent definitions	How to define, value, and measure CES to inform decision making, integrating multiple forms of knowledge and a plurality of values
CES are dynamic	CES vary in different places, and over time, as well as among different individuals and communities
Interconnectedness	Cultural aspects of landscapes are frequently entangled in ways that defy measuring a single service in isolation
Co-produced by people & nature	Reliance on social factors distinguishes them from other ES. Combination of biophysical environment, human perception, & built capital
Intangibility	Makes them complicated but not impossible to measure. Quantitative indicators can be used alongside qualitative and descriptive values
Incommensurability	Some values are not directly comparable having no common unit of measurement or standard of comparison

3.2 Understanding the importance of values

“A common way forward involves communicating peatland values, both intrinsic and measurable, to a wide audience” UK Peatland Strategy, 2018.

The concept of value is central to the ES approach, considering that ES provide benefits to individuals and societies, and values reflect the importance of those benefits (Dickinson and Hobbs, 2017). Environmental conflicts most frequently arise from the need for trade-offs between values (Hirons et al, 2016) and in the broad sense of ‘assigning importance’, valuation is part of most decisions relating to the environment and natural resources (Jacobs et al., 2016). Values are shaped by the ways people perceive, depend on, and interact with ecosystems, and many attitudes toward conservation and restoration derive not so much from “logical arguments and reasoning, but on knowledge people draw from experiences” (Scholte et al, 2016, p. 478). These experiences might include talking to peers, joining a community group, spending time in nature, or use of the ecosystem for fuel or livelihood. Current efforts to rehabilitate Bord na Móna bogs in the midlands (Section 3.3) aim to change people’s experiences and interactions with peatlands from extractive to regenerative, harnessing peat extractors’ knowledge and history of working on these bogs (DECC, 2020b). In this way, transitioning to sustainable practices can harness local knowledge, while transforming social values and norms to help increase buy-in for conservation, encourage stewardship, and minimize conflict between stakeholders (Ives & Kendal, 2014).

3.2.1 Instrumental, intrinsic, and relational values

The value of ecosystems and their services is typically expressed in ecological, economic, and socio-cultural value domains (Sarukhán et al., 2005). Ecological assessments examine how ecosystems function to contribute value (supply-side) while economic and socio-cultural valuation reflect the importance of ES to people (demand-side), expressed in monetary and non-monetary terms (Scholte et al, 2015). Socio-cultural valuation is most frequently associated with CES, although it occurs across the three value domains. These ways of expressing the value of the natural world broadly relate to intrinsic, instrumental, and relational values, which are used in varying ways as justifications for conservation. Ecosystem services only exist relative to human values, that is, an ecological function or process is only considered an ES if it contributes to human wellbeing (Hirons et al, 2016).

Environmental value can be defined in terms of instrumental or intrinsic values, that is, the value of protecting nature for human well-being (as a means to an end) versus the inherent value of nature separate from its use to humans (ethical/moral imperative) (Chan et al, 2016). This spectrum of values from anthropocentric to eco-centric has been the subject of much theoretical debate (Tadaki et al, 2017). Relational values represent a third dimension of value, which describes the diversity of relationships between people and nature that are conducive to a good life (Chan et al, 2016). The boundaries between instrumental, relational, and intrinsic value dimensions are not well-defined in reality, so it is useful to think of them as a continuum or spectrum due to the many overlaps between them (Schröter et al., 2020). These values often co-exist in people's accounts of how ecosystems are important to them, thus it is argued that all types of value justifications (intrinsic, relational, and anthropocentric) should be embraced in order to influence formation of better environmental policies and engender public support (Light, 2002). Others reflect this perspective in the environmental values debate supporting a shift away from purely instrumental values and "theoretical gridlock and toward a concern with citizen empowerment and environmental democracy" (Tadaki et al., 2017, p.1).

The relational approach to value emphasizes the rich meanings of places without using predefined categories, such as those in the ES framework. The source of value is derived from *the relationships* between humans and the environment, rather than originating from the environment only or from human society and capital (Tadaki et al, 2017). This approach focuses on supporting articulation of people's relationships with particular environments and places and is "predicated on a theoretical and ethical shift toward thinking about values through local languages and categories rather than starting with or imposing "top down" frameworks of value" (Tadaki et al, 2017, p.). Although this approach can present challenges in terms of interpreting and adequately representing meaning from the community setting to academic or policy settings, it also provides a pluralist perspective on value, which can balance economic and ecological valuations.

3.2.2 Cultural, social, and shared values

In order to understand and assess CES, it is necessary to understand the main types of cultural, shared and social values held by people[5]. Cultural values are shared principles and a shared sense of what is worthwhile and meaningful to people and are derived from the cultural heritage and practices of a society and its institutions (Kenter et al, 2015). Social values are essentially the cultural values and norms of society at large and can be used in a general sense to describe what is important to people and why, while shared values refer to guiding principles and values that are shared by groups or communities (Kenter et al, 2015). Such shared and social values resist conventional economic approaches to valuation, which assume values to be individualistic and pre-formed, as they are often shaped by social processes and expressed collectively rather than being aggregates of individual preferences (Kenter, 2019).

These social processes and values inform many of the *indirect* drivers of ecosystem change (socio-cultural, economic, governance, institutional and technological factors) that lead to the human activities which are *direct* drivers of change (land use change, pollution, climate change and others) (Díaz et al., 2020). These indirect drivers are underpinned by societal values and behaviours, thus in order to transform the trajectory of ecosystem degradation, social and cultural values must be understood and addressed (Díaz et al., 2020). Transformational change is more likely when key leverage points are activated, through for example, enabling societal visions of a good quality of life that does not entail consumption; enabling the emergence of existing values of responsibility and stewardship to effect new social norms for sustainable ecosystem management; and ensuring inclusive decision-making and the equitable sharing of benefits (Díaz et al., 2020). The inclusion of social values can be especially useful in contexts where there is uncertainty or complexity relating to the ecosystem dynamics; where issues or evidence are contested; and where there are large numbers of stakeholders (Kenter, 2019). In this way, considering social values in decision-making can support transitions to sustainability and enable transformative change and innovative governance approaches (Díaz et al., 2020).

Current thinking on CES points to the importance of a plural values-based approach in understanding how humans benefit from ecosystems (Díaz et al., 2020). Such an approach has yet to be fully operationalized in ES assessments, despite the reality that economic valuation has not achieved major changes in existing policy, nor has it halted biodiversity decline (Bullock, 2020). In order to understand the benefits provided by ecosystems, we must understand the plurality of ways in which society values them and appreciate that the type of valuation method used can influence the outcome of the

[5] See Kenter et al, 2019 for an in-depth overview of different dimensions of shared and social values

valuation (Hirons et al, 2016). Thus, valuation of ecosystem services is not a neutral process. As noted by Martín-López et al. (2014) “the methods used to elicit value actually define the values elicited [and] assessment methods are in fact value-articulating institutions”. Given the many choices inherent in valuing ecosystems, it is important to recognise that it is a deeply political process in terms of who is doing the valuing, for whose benefit, and for what purposes (Hirons et al, 2016).

3.2.3 Methods for incorporating social and cultural values

There are a variety of monetary and non-monetary methods for valuing and measuring CES, alongside approaches which prioritise co-production of knowledge and social learning (Hirons et al, 2016). Monetary valuation methods include for example, estimating the cost of replacing the health benefits provided by existing recreational environments or using the price of properties located in scenic areas as indicators (Hirons et al, 2016). However, while economic methods have raised awareness of environmental benefits, they have failed to achieve significant change in policies and are not considered adequate for describing many cultural services (Bullock, 2020). Increasingly, mixed methods research, which integrates both qualitative and quantitative evidence is advocated, alongside participatory, place-based approaches as demonstrated in Ryfield et al. (2019).

The use of social media content from platforms such as Flickr and Twitter is gaining increasing popularity for assessing and mapping CES. Analysis of such photographic datasets examine features such as charismatic species, scenic landscapes, and nature-based recreational activities, for evidence of CES distribution and perceptions of value (Hirons et al, 2016). Given that many social values are hidden or implicit, deliberation is an important way for groups to identify shared values and understand different people’s held values. Such deliberation provides opportunities for learning from interacting with other citizens and stakeholders and aims to work towards some level of consensus (Kenter et al, 2019). The following approaches focus on deliberative methods and may be used in differing contexts or integrated into mixed methods research projects as needed[6] (Kenter, 2019):

- Deliberative approaches include in-depth discussion groups and citizens’ juries.
- Analytical–deliberative methods include deliberative multi-criteria analysis and deliberative monetary valuation.
- Interpretive approaches include desk studies, analysis of media coverage or the study of cultural history from documents

[6] These methods are outlined in full in a ‘Handbook for Decision-makers’ developed by the UKNEA: dx.doi.org/10.13140/RG.2.1.4683.5281

- Interpretive–deliberative methods include participatory mapping, storytelling coupled with deliberation, and arts-based dialogue.
- Psychometric methods use questionnaires and surveys to assess the wellbeing benefits of green and blue spaces, often using subjective wellbeing indicators.

Deliberative and interpretive methods can help to build understanding and knowledge around the synergies that exist between different ES, such as water quality, biodiversity, amenity use, carbon storage and other land uses such as alternative energy. Many of these approaches ally with those outlined in recent research on measuring public engagement for water governance (Bresnihan and Hesse, 2019), sharing a focus on creation of knowledge and understanding about catchments that can inform decision-making, as well as opening a space for participation. As Waylen et al (2016, p.128) note *"*stakeholder engagement, based around people's values for and relationships to place may offer the best starting point for identifying cultural services, discussing trade-offs and seeking management strategies that are socially acceptable and practically sustainable". In this context, the main aim of valuation shifts from trade-off analysis toward developing shared understandings and dialog about plural values (Hirons et al, 2016).

3.2.4 Collaborative governance and improved ecosystem service supply

Recent research from the Netherlands demonstrates how changes in governance from top-down to more community-based, multi-stakeholder approaches involving state, market, and civil society can result in an increase in the potential and actual supply of regulating, cultural and habitat ecosystem services (Van Bussel et al., 2020). Box 1 describes the potential for increasing the capacity of peatland landscapes to be multifunctional providing a variety of ES concurrently.

Box 1 Enabling community-based management for ecosystem services at Abbeyleix Bog

Killamuck (Abbeyleix) Bog was purchased by semi-state company Bord na Móna (BnM) in 1986. Shortly afterward BnM inserted a drainage network for future industrial peat production. Further planned drainage work in 2000 met with strong local community opposition and led to an environmental case taken by the European Commission against Ireland. By 2008, the local community had negotiated a 50-year lease agreement. The community-led Abbeyleix Bog Project (ABP) was established to manage the site for conservation, recreation, and education purposes in collaboration with multiple stakeholders and a Technical Advisory Group (TAG). With the support of TAG, a series of ecological surveys and site conservation and restoration management plans were undertaken. With financial support from NPWS and BnM, approximately 64 kilometres of drains were blocked on the high bog areas in 2009 after a baseline ecotope survey was commissioned by the project. In July 2020 a follow-up ecotope survey (Fernandez and Crowley, 2020) was undertaken, which demonstrated the success of this community-led multi-stakeholder approach (Figure 9). The site is also an important and accessible amenity for recreation, education, and citizen science in the local region.

Ecological aim	Implementation	Results
-Restoration of Active Raised Bog, a priority EU habitat -Increase carbon storage capacity	-Drain blocking carried out with NWPS & Bord na Móna funding -Ecotope baseline survey (Fernandez, 2009) with funding raised by the ABP - Ecotope Surveying by Fernandez & Crowley (2020) funded by state agency and local authority	-Increase in area of Active Raised Bog -Increase in the extent of the most carbon sink effective ecotopes. -Direct CO2 emissions from high bog estimated to have fallen from 443.3 tonnes per year in 2009 to 209.9 tonnes per year in 2020.

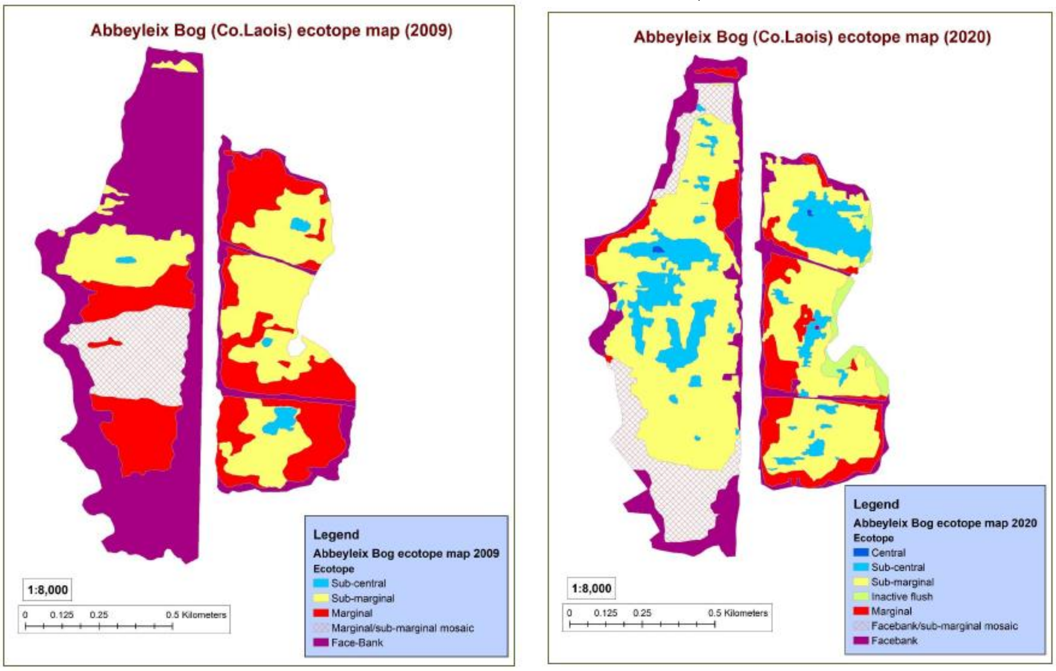


Figure 9: Abbeyleix bog ecotope maps showing increase in central & sub-central ecotopes 2009-2020. Source: Fernandez & Crowley (2020).

3.3 Cultural ecosystem services of Irish peatlands

"Understanding and accounting for cultural ecosystem services is an essentially interpretive and plural issue: what environmental spaces and cultural practices matter, where and why is always open to cultural revision and debate" (Fish et al, 2016, p.214).

3.3.1 Cultural ecosystem services

Scientific knowledge of peatlands has grown exponentially in the past two decades leading to increased awareness of their broader societal value. This awareness is increasingly reflected in public policy debates, such as those around (cessation of) turf cutting, industrial peat extraction, and planting forestry on peat soils. The BOGLAND report (Renou-Wilson et al, 2011) identified the importance of peatlands as public goods that deliver many benefits of economic and social value relating to carbon storage, biodiversity, amenity and landscape. The report provided evidence of changing attitudes to peatlands and revealed the social aspects of peatland management including the social value attached to domestic cutting of peat. It also found considerable ambiguity and lack of understanding about the incompatibility of turf extraction with peatland conservation despite general public support for the protection of peatlands. There was little public awareness of the relationship between peatlands and carbon storage nor of the contribution of drained peatlands to climate change. However, there was evidence that people living in communities around industrial peatlands wished to participate in conversations around their future, with strong support for amenity and biodiversity after-uses in evidence (Collier and Scott, 2008).

A mound of turf being left to dry. Photo: Connie O'Driscoll, Co. Mayo.

Currently in Ireland, there is a shift in cultural values and societal norms around the uses and value of peatlands. Traditionally, economic and utilitarian values relating to extraction of peat had the most value for companies like Bord na Móna and communities living beside peatlands. However, cultural aspects, such as recreation, tourism, and heritage are increasingly considered of value by emerging community groups as peatlands transform from being sites of labour and employment to sites of restoration, recreation, and conservation (Bullock and Flood, 2020). These shifts in values from unsustainable extraction of peat to management for biodiversity and ecosystem services, are largely positive and supportive of sustainable peatland management[7]. However, wider political and societal support is needed to improve awareness and understanding of the multiple values of peatlands and to halt ongoing unsustainable mining, such as that associated with the horticultural industry. The measurement and valuation of CES can create cultural change and redefine social norms around the values of peatlands and their use for the common good rather than for private economic gain.

Appendix 1 provides a reference list of peatland cultural ecosystem services developed by combining categories from the CICES and other typologies (Ryfield et al, 2019; Waylen et al, 2016). It represents

[7] An exception would be planting trees on peatlands for carbon storage. Recreation in some areas.

a starting point for thinking about CES in the Irish context, emphasising a place-based approach to considering cultural services of peatlands.

Some issues with the use of CICES for identifying CES include the complexity of categorisations when engaging with non-experts or stakeholders; the challenges of using it for local, place-based studies; and the lack of certainty around where aspects, such as local identity, sense of place, and social relations fit within the framework (Haines-Young and Potschin, 2018). It is likely such issues will be given attention in future iterations of CICES, incorporating more recent CES literature and frameworks to improve its applicability (such as those identified in Figure 7).

3.3.2 Cultural Ecosystem Disservices

While the ES framework emphasizes positive and beneficial aspects of ecosystems, some human-nature interactions are considered annoying or unwanted. These are known as ecosystem disservices, or the ecosystem functions that are perceived as negative for human well-being and are a relatively neglected aspect of CES research (Hirons et al, 2016). For example, a fear of isolated places or perceptions of them being unsafe, dislike of animals or insects, such as rats, wasps, midges, spiders, or nettles; hay fever caused by exposure to plant pollen; invasive species; and degraded environments are all recognized as disservices (Hirons et al, 2016). However, for some, wasps and spiders represent an opportunity for research and study rather than an annoyance. Equally, restoration or rewetting of peatlands can be perceived as a valued goal or as having costs or risks associated with flooding of land so incorporating disservices can raise awareness of real versus perceived threats. Thus, the degree to which something is considered to be a disservice is directly influenced by cultural perceptions and norms. Such cultural influences are often historically embedded and reflect deeply held beliefs about bogs as unhealthy places to be (for example, it was once thought that bogs exhaled vapours that caused illness and fever) or that bogs themselves were like a disease that had to be cured (Thompson, 1802).

Some ecosystem disservices result more from the actions or choices of human communities, rather than from ecosystem processes, so there is still some debate over what is included under the term (Parker et al, 2016). Research on peatlands in Scotland found that perceived negative aspects included midges, falling into bogs, getting lost, bleak landscapes, open spaces without shelter in bad weather, difficulty walking on bogs, and danger crossing them in misty or wet weather (Byg et al, 2017). Other participants acknowledged the impact that degradation of the peatland environment had on their enjoyment of the landscape, as they were conscious of species loss and CO_2 emissions from bare peat (Byg et al, 2017). Acknowledging the notion of ecosystem disservices can draw attention to the cultural values and practices, historic and current, which underlie human impacts on ecosystems and how this impacts on human wellbeing.

3.3.3 Cultural ecosystem services in Irish research

Reflecting wider trends, Irish research on peatland ecosystem services has tended to focus on provisioning and regulating services of peatlands, including water quality, carbon stocks, and flood attenuation (e.g. SWAMP and AUGER projects). Relatively little research activity has focused directly on cultural services of peatland ecosystems, although a sample of projects below shows some of the work in this area (Table 9). The NPWS Mapping and Assessment of Ecosystem Services (MAES*)* report (Parker et al, 2016) highlighted the challenges in measuring cultural aspects of ecosystems and recommended further research on CES in Ireland. In the UK, the Monitoring of Engagement with the Natural Environment (MENE) survey has been a valuable source of survey data for CES, but no such longitudinal survey about the natural environment exists in Ireland (Parker et al, 2016). However, the recommendation made in the 'Outdoor recreation plan for public lands and waters in Ireland 2017-2021' (Coillte, 2017) to develop a national recreation survey offers future opportunities to gather data for CES.

The MAES report also recommends a data gap analysis and review of the range of material relating to cultural services in Ireland and how this can be used to characterize CES at different spatial scales. CES mapping can draw on existing spatial data, geo-tagged social media data, and data gathered through stakeholder and community involvement like participatory GIS, although the latter can be costly and time-consuming to generate (Aalders and Stanik, 2016). Visitor numbers are a common method used to map and assess CES, but these may not capture landscapes and species that have intrinsic, symbolic, or spiritual value.

Table 9: Irish research projects referencing cultural ecosystem services and values.

Project	Ecosystem	Cultural services	Description
INCASE	Multiple ecosystems within catchments	Services relating to ecosystem/species appreciation; Aesthetic; Amenity; Education, science and research; and Spiritual, symbolic and artistic services	Applying the SEEA-EA at catchment scale in four study areas. Stakeholder engagement conducted throughout the project to identify data sets and prioritise services selection. Gathering data to establish process steps to develop accounts for cultural services as defined within the SEEA-EA.
Living Bog project	Peatlands/ Raised bogs	Recreation, Education, Heritage and history, Local knowledge, Tourism	A key aim of this raised bog restoration project (LIFE14/NAT/IE/000032) is to identify local stakeholders around 12 project sites to collate local cultural and land use knowledge. This informs site specific amenity & educational proposals and feeds into a local history repository managed on the project website.
WetFutures	Wetlands/ peatlands	Cultural heritage	Transdisciplinary project examining the impacts of change on wetland heritage and archaeology in the Netherlands, United Kingdom and Ireland.
CarePeat	Peatlands	Citizen science, Socio-economic benefits	Develop and test new techniques and socio-economic strategies for carbon reduction. Payments for ES (PES) schemes. Help volunteer citizen groups to assist in restoration efforts.
NatPro project	Peatlands	Provisioning services interacting with cultural services; Socio-economic benefits.	'Unlocking Nature's Pharmacy from bog land species' aims to identify species, plant extracts and molecules with potential therapeutic/ nutraceutical/ insecticidal or other commercial potential.
Deep mapping Lough Boora	Peatlands/ Industrial cutaway	Aesthetic & inspirational values, History, Heritage	A 'deep mapping' of the Lough Boora Sculpture Park, examining its historical context, ecology, and the legacy of artistic responses to this post-industrial landscape.

ES Manage	Rivers	Recreation	Project aiming to embed the ecosystem services approach into policy and decision-making for sustainable management of water resources. Synthesis of Irish freshwater ecosystem services and valuation of key ES.
Cultural Value of Coastlines	Marine/ Coastal	Sense of place Social science, Mapping	The role of culture (aesthetics, heritage, sense of place and identity) in determining human uses and values of the sea and coastlines.
Valuing Ireland's Coastal, Marine & Estuarine ES	Marine/ Coastal	Recreational, Aesthetic, Scientific & Educational services	Economic valuation of Ireland's marine and coastal ecosystems, including estimates of values for a range of marine recreational activities and aesthetic services.
NEAR Health	Marine/ Coastal	Health & wellbeing, Social cohesion, Recreation, Nature-based activities	EPA/HSE funded research investigating how nature and the environment can help society to attain and restore health, exploring how people value and experience nature, health and wellbeing.
WetlandLIFE	Wetlands (UK)	Recreation, Ecosystem disservices	Ecological, economic, social and cultural values associated with wetlands in England to better understand how to manage change into the future.

3.3.4 Overview of policy relating to cultural services and social values of peatlands

This section provides an overview of policy and legislation in Ireland that impacts and interacts with cultural ecosystem services provided by peatlands[8]. Cultural aspects of peatlands provide societal value in terms of health and well-being, education, social cohesion, tourism, and heritage value, alongside more intangible dimensions such as cultural identity, sense of place, and spiritual values. Given the broad range of sectors and policy initiatives that are relevant to the provision of CES, this overview is intended as a starting point to inform more detailed analysis of the policy landscape and how it intersects with cultural ecosystem services in Ireland (Table 10). The valuation of ecosystem

[8] For a recent summary of policies and strategies relating to peatland management in Ireland, see the Care-Peat project overview which can be accessed here.

services has multiple applications in supporting decision making, whether as part of natural capital accounting projects (e.g. INCASE project); more generally to raise awareness; as a tool for stakeholder dialogue and engagement; or to inform payments for ecosystem services and agri-environment schemes relating to peatlands. The integration of cultural and social values in these processes is important to ensure well-informed decisions are made about trade-offs between different management approaches, and all costs and benefits are taken into account.

In terms of international legal instruments implemented by Ireland in the cultural field, those of relevance include the UN Convention concerning the Protection of the World Cultural and Natural Heritage (1972); the European Convention on the Protection of Archaeological Heritage (1992); and the Ramsar Convention on Wetlands of International Importance (1971). The increasing recognition of the importance of cultural values and heritage is also expressed in the UNESCO Convention for the Safeguarding of the Intangible Cultural Heritage (2003), which Ireland ratified in 2015. This convention emphasizes non-material cultural elements or living heritage, such as cultural practices, knowledge, skills, and customs which are transmitted from generation to generation. This recognition of intangible cultural heritage is important given that many CES relate to these types of intangible social values rather than material elements of landscapes. Such values are challenging to map or monetise, but should be considered in ecosystem approaches as they influence how people behave and respond to change. The Ramsar Convention has also adopted several resolutions on culture in the past two decades, relating to local communities/indigenous peoples and integrating cultural values in wetland management.

The need for ecosystem services assessment is driven by a number of policies, including the EU 2020 Biodiversity Strategy, which has as a major target the maintenance and restoration of ecosystems and their services (European Commission, 2011). By 2020, every EU country is required to map the state of ecosystems in their territory; assess the value of the services provided by these ecosystems; and integrate these values into accounting and reporting systems at EU and national level (European Commission, 2011). This is translated nationally through Ireland's National Biodiversity Strategy 2017-2021, and the Sustainable Development Goals National Implementation Plan 2018 – 2020. These policies highlight the need to plan and manage for ecosystem services and enhance awareness and appreciation of biodiversity among policy makers, planners and decision makers, businesses, stakeholders, and the general public.

The importance of integration across sectors is also recognized in the European Landscape Convention (2000), which is implemented in Ireland through the National Landscape Strategy 2015 – 2025 (DAHG, 2015). This strategy promotes the integration of landscapes in cultural, environmental, agricultural, social and economic policies, emphasising the need for methods to assess both cultural and ecological values to ensure integrated policy making. The 'Framework for Integrated Land and Landscape Management' (An Fóram Uisce, 2020) also emphasizes the importance of an integrated, whole-systems approach for policy coherence across multiple sectors. Such an approach requires multi-disciplinary and multi-stakeholder processes in order to link environmental components (climate, air, water, soil, ecosystems) with human activities. The report recognizes the importance of catchments as multi-functional systems connecting social and biophysical elements, in which features such as rivers, streams, and wetlands form part of local communities' sense of place, contributing to their enjoyment and wellbeing (An Fóram Uisce, 2020)[9].

This need to move away from a sectoral approach to management and harmonise the implementation of policies is also reflected in the heritage sector which increasingly encourages linkages between the protection of cultural heritage and the conservation of landscapes and ecosystems. At EU level, there is increasing recognition of the interconnectedness of natural and cultural heritage and of the need for greater cooperation and information sharing between the two to facilitate more integrated landscape planning and management (Bellisari et al., 2017). For example, the integrated management of sites within the Natura 2000 network for the benefit of both tangible and intangible heritage can yield socio-economic, biodiversity and tourism benefits (Bellisari et al., 2017).

Increasingly, policy attention is also focusing on the benefits provided by cultural ecosystem services for public health and well-being (Milcu et al, 2013). Although the relationships and pathways between CES and wellbeing are complex, ample evidence exists linking the quality of the environment, its capacity to support human activities and interactions, and the health and wellbeing of the population (Hirons et al., 2016, Carlin et al., 2020). Thus, there are important opportunities to connect nature, health, and wellbeing in Ireland[10]. Future ecosystem services research in Ireland will benefit from linking with policies such as the Healthy Ireland Strategy 2013 – 2025 (Department of Health, 2013), a national framework aimed at improving the health and wellbeing of current and future generations in Ireland. The framework reflects international best practice approaches to public health which focus on prevention and a whole-system approach involving government and society. The report acknowledges and incorporates the impacts of climate change, air quality, and water quality on health, and the importance of access to the natural environment in determining health. The consideration of

[9] See Appendix 2 of this report for an overview of national and international policies advocating an integrated approach to environmental management

[10] See Carlin et al (2020) for a summary of policies and plans relating to nature-based solutions for health and wellbeing

cultural services in decision making should therefore seek to maximise health outcomes in ways which complement the provision of other ecosystem services and in line with policies across different sectors.

Table 10: Sample of policy and plans relating to CES and social values of peatlands.

Sector	Policy / Strategy	Related cultural services and values
Peatlands	Bogland report, 2011	Cultural heritage preservation; Landscape and recreation; Peat as a resource - source of energy, horticulture, cultural tradition & recreation
	National Raised Bog SAC Management Plan 2017 – 2022	
	National Peatlands Strategy 2015	
Heritage	Heritage Ireland 2030 County Heritage Plans	Cultural and natural heritage, history, aesthetic, and place-based values
	The Ramsar Convention on Wetlands of International Importance (1972) - Culture & Heritage working group	Traditional and local knowledge; cultural tradition, practices, and heritage; non-material customs/values
	Culture 2025 – A National Cultural Policy Framework to 2025	Cultural heritage and the arts
Biodiversity	National Biodiversity Strategy 2017 - 2021	Biodiversity which underpins all ecosystem services
Health and Wellbeing	Healthy Ireland Strategy 2013 - 2025	Recreation, Nature-based activities, Social relations
Recreation & Ecotourism	Outdoor recreation plan for public lands and waters in Ireland 2017-2021	Recreation, Nature-based activities, Ecotourism
	People, Place & Policy: Growing Tourism to 2025	
Education & Training	National Strategy on Education for Sustainable Development 2014-2020	Formal and informal education, Nature-based activities
	National Policy Framework for Children and Young People	
Landscape	National Landscape Strategy 2015-2025	Cultural and natural heritage; education; research; recreation and ecotourism; sense of place

3.4 Stakeholder survey and collaboration map

3.4.1 Stakeholders survey and recommendations

In order to identify gaps in stakeholder collaboration in Ireland, and any barriers to peatland management, a short survey was conducted with identified stakeholders (not all listed in the map in Appendix 3), resulting in 16 responses in total (see Appendix 4). The survey asked respondents to identify any key stakeholders missing from the initial peatland stakeholder map in order to ensure inclusivity and minimise bias. More than 40 additional stakeholders were identified in this process and added to the map (see Appendix 3 and https://adobe.ly/3uaAfQV). This map reveals the web of institutions, organisations, and community groups that influence peatland management in Ireland. This exercise was followed by three questions relating to collaboration between stakeholders; enabling management of peatlands for water quality and co-benefits; and identifying immediate management options of importance in the short term. Although the survey sample is small, some key themes and recommendations (see Section 5.2) have emerged.

1. Identify key collaboration pathways between stakeholders that could be strengthened and determine where new collaboration pathways are needed.

Some key themes and pathways identified included a need for network building and the creation of strong links and engagement between the following sectors:

Academia/Research: Collaboration between research projects (Interreg, LIFE, applied projects such as EIPs); between research institutes; and with communities and NGOs (transdisciplinary research).

Landowners and farmers: Collaboration with landowners to enhance knowledge, overcome negative perceptions of peatlands, show benefits and potential incomes. Engage with farmers on agricultural activity at blanket bog sites and with organisations like the Irish Farmers Association and Farming for Nature. More collaboration between landowners and local community groups.

Practitioners and managers: Links between local authorities and those with peatland management and ecology skills (practitioners), either through community liaison (LAWPRO, NPWS) or a local network of ecologists. Links between peatland managers and local landowners.

Communities/NGOs: Enhancement of collaboration with community groups across sectors including semi-state bodies, landowners, NGOs and researchers. Creating more links with citizen science, the National Biodiversity Data Centre, and initiatives such as the IUCN's 'Eyes on the bog' long-term monitoring project[11].

[11] Eyes on the Bog – Long-term monitoring network for UK peatlands

State agencies: Collaboration with state agencies, for example, NPWS and its ranger network, and the EPA and licensing of peat extraction.

Private sector and industry: investment from these sectors.

2. Enabling management of peatlands for water quality, climate mitigation, biodiversity, and co-benefits

Among respondents to the survey, collaboration with landowners, increased awareness and education, and financial support were considered to be the most important factors for enabling effective peatland management (See Figure 10). This may reflect the stakeholder cohort that answered the survey and thus is only an indication of relative importance.

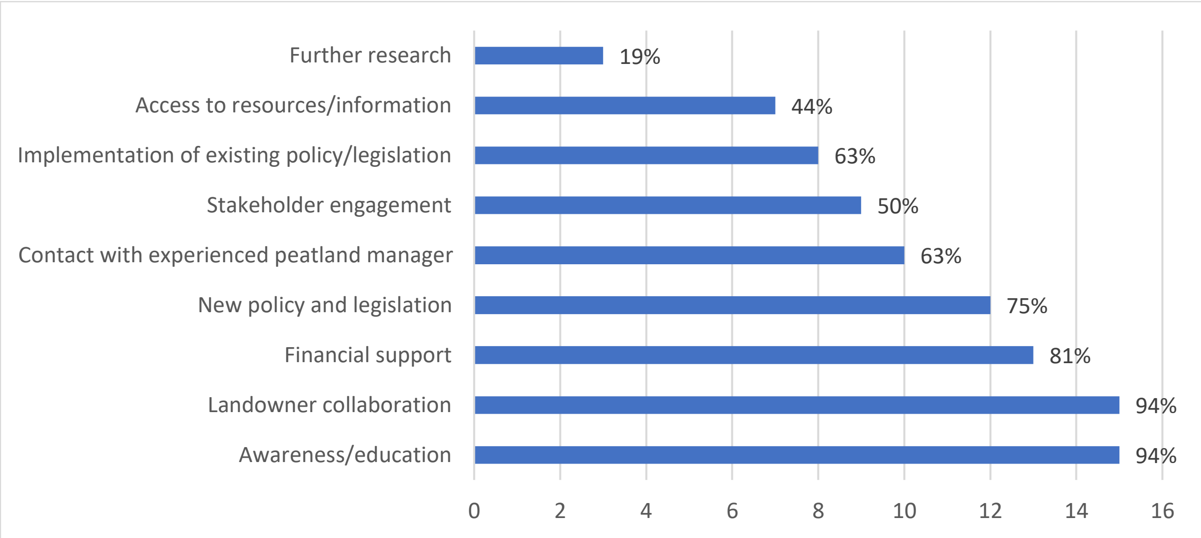


Figure 10: Responses to actions enabling management of peatlands for water quality & Co-benefits.

3. Prioritising actions for peatland management in the short term

In the final question, respondents were asked to pick the most important actions in the short-term for peatland management. The following actions relating to policy, legislation, and landowner collaboration were considered most important among this cohort:

- Meaningful engagement with landowners early in the collaborative process.
- More sustainable models for agricultural policy, such as implementing results-based payments to discourage drainage and encourage other actions to improve water quality.
- New policies to recognise ES from peatlands that could provide financial support for landowners to engage and to reward them for peatland stewardship.

- Implementing existing policy and legislation, for example, around the extraction of peat on privately owned peatlands.
- Support from local authorities – for example, Biodiversity Officers in place in each Local Authority to support volunteers.

Clear messages emerged from the survey that can be summarised as follows:

- Across the peatland stakeholder landscape in Ireland, more collaboration is needed, both horizontally and vertically, between research disciplines and projects, between sectors, and from national to local levels.
- Meaningful engagement with landowners is important early in the collaborative process.
- More sustainable models for agricultural policy, such as implementing results-based payments, and recognition and payments for ecosystem services.
- Enhance collaboration with all stakeholders

3.4.2 Updated map of stakeholders of Irish peatlands

A comprehensive map of stakeholders of Irish peatlands was compiled, and revealed the web of institutions, organisations and community groups that can influence peatland management (accessible at: https://adobe.ly/3uaAfQV and see Appendix 3). This map should be shared with the public as a draft basis for improving specific collaborations identified between stakeholders. For example, many local communities have links to the Community Wetlands Forum, while some also have links to research projects, for example Carepeat and Cloncrow Bog. It is recommended to improve this basic map after a further in-depth survey with all the stakeholders. This will then form the basis for improved collaboration between stakeholders.

3.5 Evidence gaps and recommendations

In Ireland, reimagining peatland management for the future will involve taking account of a diversity of values and perspectives in order to manage trade-offs, create synergies, and develop multifunctional landscapes. Applications of the ES approach include mapping and ecosystem assessment, valuation, development of indicators, stakeholder engagement, modelling, environmental accounting, and the development of ecological production functions (Haines-Young & Potschin, 2018). The ES approach can be used to raise awareness and promote dialogue, as a tool in landscape and catchment planning, and to develop policy instruments that take account of wider social and cultural values alongside market values. Recommendations produced as part of this review are detailed in Section 5.2.

3.6 Conclusion

While the ES approach has been criticised for its anthropocentric focus and emphasis on economic valuation, it also provides useful tools and methods to support sustainable management of ecosystems. With demand for CES expected to grow in industrialised societies, the process of deliberation and co-production of knowledge involved in CES research can help identify future conservation and management options for peatland habitats. Ecosystems have multiple values, which are continually being constructed through the interactions of individuals, institutions, and societies with nature. The very process of identifying and measuring values potentially alters the interactions people have with nature and redefines what is and is not of value. Therefore, the design of these processes is crucial in ensuring processes that are empowering, equitable, and inclusive. Such approaches can also help challenge the privileged position of economics as the central discipline for guiding policymaking and practice (Chan et al., 2018).

In Ireland, questions of value will be key to deciding future land uses of peatlands and such values require deliberation and discussion between various stakeholders. Understanding the full range of ecosystem services provided by peatland landscapes can help to shift the focus from provisioning ecosystem services towards regulating and cultural services, which provide value to society in the long term. This would allow for a more complete representation of values including cultural, relational, shared and social values; values of different stakeholders including communities, scientists, and policy makers; local, regional, and global scale values; and future bequest and option values. Ultimately, perhaps less important than what framework, concept, or approach is used to assess cultural and social values, is that they *are* included in some way in decision making despite the challenges involved. This can help to foster new and transformative types of societal values that support the sustainable management of peatlands and maintain their important contribution to human wellbeing in the long term.

4 Alternative Management Options of Degraded Peatlands

The evaluation and application of innovative technologies and alternative management options for degraded peatlands to improve water quality, whilst enhancing other peatland ES, should consider the existing land use and the sensitivity and vulnerability of the surface water and groundwater receptor.

Irish peatlands currently have multiple land uses, i.e. afforestation (28%), agriculture (26%), industrial cutaway (5%), rehabilitated cutaway (1%), turbary (25%) (Table 1). While the overarching objective of the European Union Water Framework Directive (WFD) (Directive 2000/60/EC) is to achieve 'good' status for all waterbodies, and maintain 'high' status where they exist, some waterbodies require additional protection by virtue of their location in a protected area or their function as a drinking water or bathing water. Under the requirements of Article 6 (and Annex IV) of the WFD a Register of Protected Areas was established to designate:

1. Areas for the abstraction of drinking water
2. Areas for the protection of economically significant aquatic species
3. Recreational waters
4. Nutrient sensitive areas
5. Areas for the protection of habitats and species where the maintenance or improvement of the status of water is an important factor in their protection.

Management approaches need to be established to restore/maintain water quality to the standard determined by the WFD and Habitats and Birds Directives (Directive 92/43/EEC and Directive 2009/147/EC respectively) and that are required by the Drinking Water Directive (DWD (80/778/EEC) as amended by Directive (98/83/EC) for the range of peatland users.

4.1 Extracted peatlands

Summary of key messages

- Current management interventions for peat extraction include silt ponds, rehabilitation and reclamation for new land uses.
- Rewetting is not required under licencing for rehabilitation and revegetation occurs through natural succession. Typically vascular plants rather than bog indicator species return, even after a 30-year period.
- Restoration prescribes increasing the water table to within 10 cm of the surface and offers the best long-term water quality benefit, in addition to climate change and biodiversity benefits.

- Alternative land use with rewetting is the optimum solution for industrial peat extraction and where unfavourable site modifications could not support restoration, new habitat types, i.e. mosaics of bog/ fenland, woodland, heather and scrub/ open water are proposed.
- Other techniques that offer potential include biochar filters, overland flow, constructed wetlands and chemical purification.
    - Overland flow involves diverting runoff to a vegetated area, which has the additional benefits of particle trapping and nutrient uptake by the vegetation.
    - Constructed wetlands have been shown to purify extraction runoff reducing nutrients and suspended solids, sequestering carbon, producing biomass, and promoting biodiversity.
    - Chemical purification shows promise for immobilising P and removing DOC and suspended solids in peatlands.
    - Biochar is capable of absorbing organic and inorganic nutrients, heavy metals and other contaminants.
- Based on a trial study, it was concluded that industrial cutaway peatlands are not suitable for raw water storage as reservoirs.

Current management practices and mitigations for peat extraction include silt ponds, rehabilitation, and reclamation for new land uses, which are discussed below. Silt ponds in particular target suspended sediment and do not consider other contaminants, such as ammonium which enters aquatic ecosystems downstream of peat extraction sites.

4.1.1 Silt or sedimentation ponds

Silt or sedimentation ponds are installed at site preparation, whereby all excavated ditches are channelled toward the ponds. While design itself is site specific, typically widths of 8–12 m and depths of 1.5 m are observed. Flow velocity is controlled by the diameter and gradient of inlet and outlet pipes but targeted to 10 cm sec^{-1}. While multiple refinements have been proposed involving several basins in series / parallel, flow regulation structures and geotextile curtains (Samson-Dô and St-Hilaire, 2018, Hafdhi et al., 2020), the most critical is regular maintenance of the ponds (Bord na Móna, 2020b). Good operational practice also does not always ensure adequate sediment removal as sediment size and high rainfall events can cause export (Es-Salhi et al., 2013). Additionally, DOC and other nutrients are largely not trapped in sediment ponds resulting in export also.

Sedimentation pond at peat extraction site. Photo: Florence-Renou Wilson

4.1.2 Other management options

Other techniques to mitigate shorter term impacts include overland flow, constructed wetlands, chemical purification, and biochar filters. The overland flow technique is employed to purify runoff water during extraction and rehabilitation and involves diverting runoff to a vegetated area, which has the additional benefits of particle trapping and nutrient uptake by the vegetation (Heikkinen et al., 2018, O'Driscoll et al., 2014b). However, adsorption effectiveness is a function of the site condition, slope and hydraulic retention time (Heikkinen et al., 2018, O'Driscoll et al., 2014b). Constructed wetlands are the preferred mitigation approach for peat extraction in Finland where natural peatlands are not available for the overland flow technique (Mohammadighavam et al., 2016). Wetlands have been shown by numerous studies to purify extraction runoff reducing organic N, total N and suspended solids (Postila et al., 2014, Ronkanen et al., 2017). In addition, wetlands can enhance removal of other nutrients, sequester carbon, produce biomass and promote biodiversity thereby providing multiple environmental, social and economic functions (Geurts et al., 2020, Worrall et al., 1997).

Chemical purification methods are being researched in Finland and are widely seen as one of the best available techniques (Heiderscheidt et al., 2013). Metals salts, such as ferric sulphate can remove high and low molecular weight fractions of DOC (Heiderscheidt et al., 2016). Of organic coagulants, chitosan and tannin-based coagulants have been shown to be most successful at removing suspended solids although not as effectively as metal counterparts. Chemical purification methods have been researched in Ireland (Callery et al., 2015) and considerable promise has been shown by aluminium water treatment residual for P immobilization in a peat environment.

Biochar, formed by heating organic material, such as wood under low oxygen conditions, is capable of absorbing organic and inorganic nutrients, heavy metals and other contaminants and is used extensively in water treatment and wastewater. While there is limited research on its use in treating peat extraction wastewater it has been shown to been effective for runoff from forest harvesting sites (Saarela et al., 2020).

4.1.3 Rehabilitation and restoration

Rehabilitation involves allowing a site to naturally recolonize with vegetation to stabilise the bare peat surface and minimise pollution to air and water. Rehabilitation forms part of the requirements of decommissioning and licence termination, and monitoring verifies no outstanding environmental liability. Rehabilitation may not necessarily be the 'optimum' solution as it relies on the revegetation by natural succession, which has been shown to have preference for vascular plants with very few bog species returning, even after a 30-year period (Priede et al., 2016, Rowlands and Feehan, 2000). Additionally, GHG monitoring is not required at these sites, whereby a site could be shown to be a carbon sink; or for monitoring of DOC, which has water treatment implications for water treatment plants abstracting downstream.

Restoration is the return of the site to its original state of abiotic (hydrological regime, surface topography and chemical status) and biotic (flora and fauna) conditions. Restoration of a drained peatland involves increasing the water table to within 10 cm of the surface (Kelly and Schouten, 2002), via backfilling drains, dam construction, ditch blocking and ridging (Mackin et al., 2017). It is believed to offer the most benefit regarding climate change and biodiversity, while the benefits to water quality may take up to 30 years. Most benefits are likely to be achieved via a combination and configuration of several processes/mitigations.

4.1.4 Alternative land uses

In some instances, alternative land uses are proposed for decommissioned extraction sites, such as agriculture, i.e. grassland, cropland and forestry, and windfarm development. Evidence has shown that the alternative land use is the optimum solution for industrial scale peat extraction and rewetting is preferable for maximum benefits. Where unfavourable site modifications would not support restoration, e.g. shallow peat depth, a new habitat type including mosaics of bog/ fenland, woodland, heather and scrub/ open water are proposed (Renou-Wilson et al., 2011, Mackin et al., 2017).

An extraction site which has been flooded to create an area of wetland. Photo: Catharine Pschenyckyj.

4.1.5 Cutaway peatlands as reservoirs

The idea of using industrial cutaway peatlands for raw water storage came from an initial study carried out with the objective of mitigating the impact on residence time in Lough Derg resulting from year-round abstraction from the North East quadrant of the lough. This would permit reduced lake abstraction during two summer months, with the balance being made up water held in storage in the cutaway. A cutaway peatland located at Garryhinch (north of the R423 Portarlington to Mountmellick road) was thoroughly investigated for that purpose (Irish Water, 2016). Subsoil investigation results indicated several challenges for the construction of embankment and the reservoir underfloor drainage conditions due to:

1) The presence of karst bedrock in two relatively large areas of the site

The karstified bedrock has itself several risks including increased seepage through the weathered rock and may include further karstification with the risk of caverns occurring with the consequent potential for collapse but also the risk of unpredictable occurrence, extent and depth of underground cavities which may lead to inadequate foundation support for reservoir embankments and base. Even the sludge lagoons proposed to treat water works sludges have a high risk of failure at the bases and embankments due to karst features underneath.

2) Generally, more elevated water table than expected (close to the ground surface).
3) Non-uniform permeability rate over short distance.

The silt and clay present on site is very heterogenous and may not provide a 100% seal with areas of higher permeability acting as a drain resulting in drainage of the stored water in the reservoirs or as route for rapid development of groundwater pressures;

4) Greater than predicted variability in depth to bedrock.
5) The prospect of difficult dewatering conditions based on groundwater pumping tests.
6) The prospect of difficulty excavation and disposal of peat.

The remaining peat is very wet, and its excavation and disposal has serious environmental consideration in itself not least for water quality (during dewatering but also due to weather-related events causing peat to become slurry) but also climate with the likely loss of huge amount of the carbon due to drying of the peat. The technical excavation and disposal of peat is also not without difficulties given the potential for instability even at very low slope.

Adding other environmental risks associated with existing suspended solid pollution control and the risk of transferring invasive species into river systems, the report concluded that it was not recommending that storage of raw water at Garryhinch is pursued.

While this is based on the thorough investigations of one cutaway one, it has been demonstrated in many studies that cutaway bogs are heterogenous in their edaphic and sub-peat geological properties (Renou-Wilson et al., 2008), and similar difficulties would be encountered in other nearby cutaway leading to the conclusion that overall industrial cutaway peatlands are no suitability of such area for raw water storage.

4.2 Commercial Forested Peatlands

Summary of key messages

- Multiple interventions have been suggested for afforested peatlands, but guidelines are lacking when it comes to a clear decision tree for the intervention selection process, based on scientific data that can provide pollution prevention solutions in catchments with sensitive receptors.
- Best Management Practices are established for forestry operations on peatlands, but are not site specific or scientifically robust, resulting in pollution events following clearfelling.
- Novel practices considered include retrofitted buffer zones/ overland flow systems, whole tree harvesting, continuous cover forestry (CCF), and a refinement of the use of brash mats.
- CCF may be advantageous in sensitive catchments because of reduced risk of windthrow, reduced soil carbon losses to air and water, better soil fertility, and reduced water table fluctuations.
- Grass seeding could be used to enhance the natural regeneration process in a clearfelled catchment, thereby accelerating P uptake and reducing P export.
- Biochar filters have been used to purify runoff from clearfelled forests.
- Restoration for afforested peatland sites is unpractical and alternative replanting models offer more optimistic outcomes.

4.2.1 Best Management Practices

Best Management Practices (BMP) are established for forestry operations, which include strategic location for landings and turntables; reduced felling coupe[12] sizes for better dilution; short extraction routes; site specific extraction equipment; optimum weather conditions; and appropriate use of brash mats, sediment traps and buffer zones (Forest Service, 2000). However, BMP in Irish forestry are derived from those in existence elsewhere, and from qualitative local knowledge rather than from quantifiable scientific data for blanket peats (Finnegan et al., 2014). Two studies from the forestry research site in the Burrishoole catchment described elevated total organic nitrogen (TON) and total reactive phosphorus (TRP) following clearfelling even when BMP were employed (Rodgers et al., 2010, Finnegan et al., 2014), and O'Driscoll et al. (2016) and Ryder et al. (2014) have also demonstrated elevated N, TRP, DOC and POC.

O'Driscoll et al. (2014b) retrofitted a buffer zone as an overland flow system and demonstrated reduced P export from a felled site, although as for the overland flow techniques described for peat

[12] A small area of forest within a compartment that is harvested in a single operation.

extraction sites, hydraulic retention time is a critical factor. Additionally, alternative harvesting techniques, such as whole tree harvesting, and continuous cover forestry have shown promise. With whole tree harvesting all brash material is removed from the site thereby reducing a potential nutrient source (Asam et al., 2014, O'Driscoll et al., 2014a).

Riparian areas and buffer zones, while firmly set in current guidelines, were not in place at the onset of afforestation (1960s–1980s) and so, many trees are planted up to the waterbody edge. Buffer strips have been reported to obviate the impact of soil erosion from forestry activities however their presence is not the only factor, and variables such as width, slope, soil type, local rainfall trends and vegetation structure are equally as important (Ryder et al., 2014). Brash mats (also essential BMP) were reported to give rise to the highest P concentrations following a clearfelling event in Co. Mayo (Rodgers et al., 2010). A refinement of the use of brash mats could include the arrangement of brash windrows across the gradient rather than with the gradient (Asam et al., 2012).

4.2.2 Continuous Forest Cover

In continuous cover forestry (CCF) the aim is to always to maintain a forest canopy by utilising natural processes, such as forest succession and natural regeneration of trees. There is limited research available, but the theoretical benefits are greater windthrow resistance, reduced soil carbon losses during harvesting, better soil fertility and reduced soil CO_2 emissions (Nieminen et al., 2018). Additionally, the associated rise in water table following a clearfell would be eliminated, avoiding the reduction/oxidation conditions in surface peat associated with felling that give rise to enhanced P and DOC exports (Kaila et al., 2014, Nieminen et al., 2015). CCF could be particularly advantageous in sensitive catchments (i.e. drinking water or ecologically sensitive catchments) because of reduced risk of siltation / nitrate flushes (Wilson et al., 2018).

4.2.3 Grass seeding

O'Driscoll et al. (2011) developed the novel grass seeding technique as a method to enhance the natural regeneration process in a forest clearfelled blanket peat catchment using native species *Holcus lanatus* and *Agrostis capillaris*. There, 88–95% of P was retained in grass seeded areas demonstrated at the flume and field scale (O'Driscoll et al., 2014a, Asam et al., 2012). Furthermore, Asam et al. (2020) also highlighted that seeded grasses are a major sink of N on harvested blanket peatland forests.

4.2.4 Biochar

Biochar has been found to be effective for purifying runoff from a clearcut forest with 58% reduction observed (Kakaei Lafdani et al., 2020). As an afteruse, the exhausted biochar could be applied to newly afforested sites as a soil amendment that would slowly release nutrients back into the soil for the newly planted trees (Köster et al., 2020, Zhao et al., 2019).

4.2.5 Replanting approaches

With regard to longer term management of afforested peatlands, research has shown that restoration for afforested peatlands is not as straightforward, and alternative replanting models have been suggested (Lundholm et al., 2020b). Four alternative replanting approaches were described in place of the 2,500 stems ha^{-1} replanting standard:

a. **Lodgepole pine fibre** planted at 1600 – 2000 stem ha^{-1} is a lower intensity management option, which still produces pulpwood but does not require any management interventions between planting and felling, and clearfelling can be expected at the age of ~50 – 60 years. Coillte have adopted categorising low yield class areas for wood fibre production and appear to have settled on a 2,000 stems density, a value that must be approved by the Forest Service at the licence application stage.
b. **Lodgepole pine biodiversity** planted at 1100 stem ha^{-1} allows existing timber to be extracted while transitioning the stand to a more natural low stocked forest. Following plantation there should be no further management interventions but it is acknowledged that naturally regenerating lodgepole pine and rhododendron may require removal.
c. **Nephin thin** is established by heavily thinning a site (63–75% reduction) with a density of approximately 450 – 600 stems ha^{-1} remaining.
d. **Modified kronoberg** suitable only for blanket peat sites of peat depth <0.5 m and recommended Sitka spruce yield class of 16. A mixture of 54% Sitka spruce and 46% downy birch at a density of 2500 trees ha^{-1}.

4.2.6 Strategic forest management decisions support tool

With multiple possibilities for afforested peatlands, a clear decision tree with guidelines for future management options is warranted with BMP based on scientific quantitative data that can provide pollution prevention solutions for afforested peatlands in catchments with sensitive receptors and defined by the Register of Protected Areas.

Implementation of a strategic forest management decisions support tool, which considers source load apportionment (nutrient and suspended sediment export) at the stand and catchment scale across all forestry operations, could assist (Mockler et al., 2017, Lundholm et al., 2020a). Ideally a decision tree for afforested peatland should consider three key pillars:

1) Carbon management: whether a second rotation will create a net GHG sink, sufficient to offset what would be lost during cultivation, and whether additional cultivation or nutrients would be required.
2) Is the coupe in a drinking water protected area?

3) Is the coupe within the zone of influence of an ecologically sensitive receptor?

The cumulative assessment of these three pillars will determine the future management of these sites.

4.3 Agricultural peatlands

Summary of key messages

- Rewetting coupled with cessation of grazing and a subsequent vigorous growth in vegetation has demonstrated benefits for carbon cycling.
- European Innovation Partnership (EIP) Locally Led Schemes are supporting farmers in developing innovative approaches to agriculture that aim to reduce environmental impacts and, therefore, enhance habitats for sensitive receptors. Examples include targeted fencing, strategic positioning of drinking troughs, and rewetting utilising peat plugs, and flow reduction via timber weirs.

(Renou-Wilson et al., 2016) identified management techniques on nutrient poor organic soils with poor drainage, such as rewetting coupled with cessation of grazing and a subsequent vigorous growth in vegetation that resulted in CO_2 removals (from the atmosphere) and decreased methane emissions.

European Innovation Partnership (EIP) Locally Led Schemes, such as the Pearl Mussel Project (https://www.pearlmusselproject.ie/), are supporting farmers in developing innovative approaches to agriculture that aim to reduce environmental impact and, therefore, enhance habitats for sensitive receptors. Simple practices, such as targeted fencing, strategic positioning of drinking troughs, and rewetting utilising peat plugs and flow reduction via timber weirs are being employed by farmers with the aim of increasing their 'farm scores' (McLoughlin et al., 2020). These projects are in their infancy to some extent and so scientific evidence as such is not yet available. Similarly, the Hen Harrier Project (also an EIP project) is working with farmers to develop an effective model for future sustainable management of Hen Harrier areas, provision of quality habitat and to work against wildfires, which cause a high level of risk to the Hen Harrier. The Dunhallow Farming for Blue Dot Catchments EIP are pursuing the restoration and protection of high status waterbodies within their project area by employing bespoke high status measures and nutrient management strategies, developed under previous high status farm focused conservation projects in the area. Development of quality habitat and vegetation is being promoted in the EIPs and has a direct impact on water quality downstream, reducing suspended sediment and nutrients.

5 Strategic guidance and resources for future integrated management of peatlands

Summary of key messages

Four priorities have been identified in order to meet the aim of optimizing water quality returns from peatland management while delivering co-benefits for climate and biodiversity. Within these priorities, solutions have been provided or key actions have been suggested.

Priority 1- Including social values in peatland management and stakeholder collaboration (Section 5.2)

☞ *Incorporate social and cultural values into research, policy, and decision making*

1.1 Encourage research from social sciences, humanities and arts when commissioning research.
1.2 Develop shared knowledge of different areas of expertise at all stages of projects and co-develop research objectives, methods and outputs.

☞ *Identify evidence gaps and encourage research on CES and social values of peatlands*

1.3 Identify potential data sources to support CES mapping or generate new sources if needed
1.4 Identify suitable indicators, data sources and methods for CES mapping.
1.5 Identify whether the ecological state of peatland ecosystems positively or negatively affects the delivery of cultural services, at different types of peatland habitat.

☞ *Enhance collaboration with all stakeholders*

1.6 A map of Irish peatland stakeholders should be published and shared with the public as a basis for improved collaboration between stakeholders (Available here https://adobe.ly/3uaAfQV).
1.7 Conduct a stakeholder analysis to identify key collaboration pathways, assess the quality of relationships and recommend new areas for collaboration.
1.8 Create support networks and bridging organisations.
1.9 Ensure meaningful engagement and participation starts from early in the collaborative process.
1.10 Stakeholders should engage in collaborative actions including awareness raising; advice, training, and knowledge transfer; and building a common platform, such as a National Peatland Group.
1.11 Give priority to widening sources of funding in order to establish long-term monitoring, alongside creating a new model of co-designed research that integrates citizen science.

☞ *Mechanisms to support inclusive and collaborative governance and encourage bottom-up approaches to peatland management/conservation*

1.12 Build local community capacity in understanding, monitoring and assessment of peatlands through training, citizen science initiatives and knowledge exchange.

1.13 Develop structures and supports for community groups applying for funding.
1.14 Develop strong partnerships between state agencies and community groups and networks in an open, transparent, two-way process of information sharing.
1.15 Encourage public sector organisations to have dedicated community liaison staff.
1.16 Encourage action research approaches, i.e. research that is initiated and driven by communities, and involvement in all aspects of the research.

☞ *Integrated management- including qualitative social science methods in ecosystem service assessment and valuation*

1.17 Encourage integrated approaches to ecosystem assessment and valuation, combining ecological, cultural, economic, and ethical value dimensions

Priority 2- Identify land use/ land use change impacts and co-benefits of management options (Section 5.3)

☞ *To give a coherent vision of the mix of peatland utilisation, their impacts and the available choices (see Table 11).*

Priority 3- Implement existing policies and ensure full compliance with relevant regulations (section 5.4)

☞ *To prevent deterioration of water quality and apply adequate mitigation measures*

Conservation and biodiversity governance:

3.1 Urgently meet the objectives for designated protected peatlands under the Habitats Directive and restore all raised and blanket bogs SAC.
3.2 Provide sufficient funding via new funding mechanisms for peatland restoration schemes which include long term monitoring, support for peatland community schemes and promotion of citizen science.

Environmental governance:

3.3 The legal status of all peat extraction activities needs to be urgently finalised together with the implementation of evidence-based mitigation measures.

Agricultural and forestry governance:

3.4 Prioritise rewetting of nutrient rich organic soils that act as hot spots of both CO_2 and N_2O.
3.5 Provide incentives to rewet agricultural peat soils.
3.6 Assess the combination of new CAP instruments now available, to enable low-emission peatland utilisation suitable for a range of stakeholders.
3.7 Ensure decisions on future land use are site specific accounting for ecosystem services and sensitive receptors.

Water governance

3.8 Recognise peatland degradation status in the River Basin Management plans and monitor all catchments, especially with regards to DOC and ammonia emissions.

Priority 4- Investigate the current and future risks; monitor actions; and research alternatives (Section 5.5)

☞ *To identify gaps in knowledge to better inform decisions.*

Environmental and land use research

4.1 Assess and prioritise key research questions for land use and land use change affecting peatlands including windfarm, forestry and agriculture.
4.2 Utilise an ecosystem approach (used to improve ecological impact assessment) for future peatland research priorities.

Long-term monitoring and datasets repository

4.3 Track the success of interventions for integrated peatland management to develop robust guidance.
4.4 Make a collection of restoration/rewetting projects and peatland datasets available to all stakeholders.
4.5 Develop standardised methodology and training capacity that enables individual peatland sites to be consistently monitored and thus creating a network of comparable sites.
4.6 Establish a national peatland observatory / research site network to support long-term research and initiate large scale pilot studies/catchment interventions; in conjunction with a common research protocol.

Innovative sustainable management options

4.7 New, well-designed experimental field studies with replications should be established at various bogs across the country with more suitable environmental characteristics (i.e. hydrological status and soil properties should be monitored prior to Sphagnum inoculation), in order to trial paludiculture on industrial peatlands.

Identifying Resources:

- The costs of restoration measures is difficult to calculate with precision, while the cost of not restoring can be alternatively considered via proxies.
- It is critical that the government provide a long-term financial framework to secure the continuity of the sustainable management of shared peatland resources, including both designated (SAC, NHA) and undesignated peatlands.
- Carbon credit schemes could provide financial intervention, as well as mechanisms by which businesses, organisations and individuals could invest in land-management and restoration schemes. Carbon offsetting schemes would not only deliver significant climate change mitigation, but would also support habitat conservation, provide cleaner water, and generate new sources of income for farmers/ landowners.

5.1 Scope

This final chapter considers approaches to help meet the environmental challenge of managing our peatlands sustainably so that threats to water quality (surface and drinking), climate and other ES (biodiversity etc.) are reduced. With the overall aim to optimize water quality returns from peatland management while delivering co-benefits for climate and biodiversity, this chapter details a strategic guidance and resources for future integrated peatland management in Ireland, which could be incorporated into future changes in land use and peatland utilisation.

Given the importance of peatlands in the Irish landscape, and their significance as a source of opportunity to improve water quality, biodiversity and climate impacts, the following four key priorities have been identified to guide future peatland management in Ireland:

1. **Including social values in peatland management and stakeholder collaboration**

   ☞To enable social values and perspectives to be identified, assessed and included in peatland management and decision making, and lift barriers by enabling collaboration between stakeholders

2. **Identify land use/ land use change impacts and co-benefits of management options**

   ☞To give a coherent vision of the mix of peatland utilisation, their impacts and the available choices

3. **Implement existing policies and ensure full compliance with relevant regulations**

   ☞ To prevent deterioration of water quality and apply adequate mitigation measures

4. **Investigate further the current and future risks; monitor actions; and research alternatives**

   ☞ To identify gaps in knowledge to better inform decision

5.2 Priority 1: Including social values in peatland management and enhancing stakeholder collaboration

These recommendations follow the review of social values for peatlands outlined in Section 3. They provide some guidance on how best to elicit, assess, and include the wide range of values and perspectives for sustainable peatland management and decision making.

5.2.1 Incorporate social and cultural values into research, policy, and decision making

- Interdisciplinary and transdisciplinary research:

  ☞ **R 1.18: Encourage the inclusion of research from social sciences, humanities, and the arts alongside economic and ecological disciplines when commissioning research to guide conservation and sustainable management of peatlands.** Transdisciplinary research which goes beyond academia should also be supported, to encourage collaboration with public and private sector organizations, practitioners of peatland restoration, governments, and local communities.

- Co-production of knowledge:
  ☞ **R 1.19: Develop shared knowledge of different areas of expertise at all stages of projects and co-develop research objectives, methods and outputs from the start.** This enables effective conservation decision-making, rapid social learning and adaptation to changing conditions (Bennett et al, 2017). Local knowledge about peatlands can complement technical scientific knowledge and together, this can contribute to more acceptable and sustainable management and policy (Bennett et al, 2017). Integrating knowledge in this way can help to break down barriers, creating a shared sense of responsibility for implementing plans and policies (Reed et al, 2018).

5.2.2 Identify evidence gaps and encourage research on CES and social values of peatlands

- Data, inventories, and monitoring of CES of peatlands:
  ☞ **R 1.20: Identify potential data sources to support mapping of CES of peatlands and generate new sources where necessary** (Aalders & Stanik, 2016). Existing sources include national data that could inform the supply of CES, such as the presence of wildlife or habitats/ landscapes through designations, or cultural heritage features.

- CES Indicators*:*
  ☞ **R 1.21: Identify suitable indicators for CES of peatlands so results of assessments and valuations can be communicated to decision makers and practitioners in conservation management. I**dentifying CES indicators[13] for peatlands is an important step so they can be included in conservation management plans, environmental reports/screenings, and landscape planning. These should include supply-side indicators (measuring the location and ability of peatlands to deliver CES), and demand-side indicators (measuring the preferences and values of populations).

- Research on the impact of restoration, rewetting, or ongoing degradation of peatlands on the provision of cultural services:

---

[13] The James Hutton Institute developed a suite of CES indicators for Scotland which rely on existing data or 'proxies', and could be adapted to the Irish context. Potential sources of data include Ireland's open data portal, Historic Environment map, NPWS, Coillte, Bord na Móna, Failte Ireland surveys (Aalders & Stanik, 2016)

☞ **R 1.22: Identifying whether the ecological state of peatland ecosystems positively or negatively affects the delivery of cultural services**, and differences in provision of CES at different types of peatland habitat e.g. coastal blanket bogs, raised bogs, heathland, industrial cutaway.

5.2.3 Enhance collaboration with all stakeholders

- Collaboration between stakeholders:

In order to address the concerns raised by the survey (Section 3.4), established organisations with the power to facilitate networking and knowledge sharing should be identified, in order to contribute to the delivery of the key recommendations below.

☞ **R 1.23: A map of stakeholders of Irish peatlands should be published and shared** with the public as a basis for improved collaboration between stakeholders (Available here https://adobe.ly/3uaAfQV).

☞ **R 1.24: Conduct a stakeholder analysis to identify key collaboration pathways, assess the quality of stakeholder relationships and recommend new areas for collaboration.**

The peatland stakeholder map is a first step in listing the broad range of stakeholders involved in water and peatland management in Ireland (see Appendix 3 and https://adobe.ly/3uaAfQV). The next step in this process is to use the map as the basis for a more comprehensive stakeholder analysis, to categorise and assess the quality of stakeholder relationships and the types of information flows and patterns of engagement between agencies, NGOs, local authorities, community groups and others. Stakeholder analysis can reveal which stakeholders are interacting with each other, how often, where the conflicts are, who is centrally placed and who is more marginalised, in order to bridge knowledge gaps (Luyet et al., 2012). It can also reveal the potential for coalitions between stakeholders or identify new stakeholders, map levels of access to resources, create understanding of political influence on projects, and other issues relating to power and equity. This can help to identify and address entrenched power relationships in the participatory process, as recommended by Bresnihan and Hesse (2019). Such an analysis should use best practice methods and techniques (e.g. Social Network Analysis for assessing relationships between stakeholders) to understand the challenges and limitations of existing methods and identify the risks involved. The choice of participatory techniques and methods can depend on multiple factors including knowledge of stakeholders, local cultural and social norms, and past events that might influence the process (Luyet et al., 2012).

☞ **R 1.25: Create new and support existing networks and bridging organisations.**

Research on Scottish peatlands found that flows of scientific knowledge relied on social connections and networks between science and policy teams and communities, in order to generate policy-relevant evidence in a more collaborative and systematic way. Boundary and bridging organisations were found to play a key role in knowledge exchange and investment in trust-building processes was essential for achieving impact from research (Reed et al, 2018). Bridging organizations are described as "organizations whose activities mediate connection between people or groups who would otherwise have not been connected […] facilitating coordinated and consistent management action" (Rathwell and Peterson, 2012). Such organisations have been found to positively correlate with engagement in water quality management activities, facilitating coordinated approaches and management of shared resources (Rathwell and Petersen, 2012). The authors of this study also found that the number of collaborations within stakeholder networks is positively correlated with the extent of involvement in water management and confirmed the importance of bridging organizations in creating such connectivity across regions. Thus, in the Irish context, identifying bridging organisations, and creating and funding new or existing bridging organisations can help to support and maintain a collaborative peatland network.

☞ **R 1.26: Ensure meaningful engagement and participation early in the collaborative process.**

Public and stakeholder participation is described as "a complex system, with multiple purposes, interactions, meanings, degrees of involvement, methods, and solutions that are specific to each context and project" (Luyet et al., 2012). Thus, meaningful engagement is not achieved through one-size-fits-all approaches. Bresnihan & Hesse (2019) offer guidance on the design and facilitation of effective public engagement in water management in Ireland, which is also relevant to peatland management. The authors recommend supporting public participation processes, which incorporate three key principles of effective public engagement relating to power, knowledge, and scale. These principles highlight the importance of addressing power imbalances between different individuals and stakeholder groups; incorporating and integrating multiple forms of knowledge, including local and practitioner knowledge; and addressing issues of scale in terms of how national processes and governance can limit local decision-making on peatland management. These principles are important given that not all stakeholders benefit equally from ES and power relationships are a key factor influencing the ability of individuals or groups to access ES. In concurrence with the authors, a useful exercise would be to conduct an evaluation of current peatland public engagement initiatives based on the principles identified above. These initiatives can be examined for compliance with good governance principles of accountability, transparency, equity, inclusiveness, responsiveness, effectiveness, and efficiency, which are necessary to support public engagement. This will lead to more inclusion of communities and individuals in decision-making around peatland management and water resources from early in the process, which is essential to build trust (Bresnihan & Hesse, 2019).

☞ **R 1.27: Stakeholders should engage in collaborative actions** including awareness raising; advice, training, and knowledge transfer; and building a common platform such as a National Peatland Group.

Stakeholders collaborative actions are required to integrate all ES values, scientific as well as social. New methods have been developed to integrate social and ecological data. Of note, a process called 'anticipation and engagement' can be used to identify and lift barriers to sustainable management. Via 'anticipation', the available literature and local knowledge is first gathered to outline the main 'factors' at specific sites and fit the project into an overall coherent vision of integrated peatland management. Next, 'engagement' refers to the exploration of these factors with the community itself, thus enabling the next step to be facilitated: that of development an integrated peatland management which would include specific key performance indicators that should be monitored to feedback into the process. To address these key collaborative actions, established institutions must first identify their potential roles and adopt new remits to ensure the delivery of real action and positive outcomes with regards to integrated management of peatlands (see more under 'Resources' section).

- Stakeholder research collaboration:

It should be noted that since 2019, Ireland has significantly enlarged the funding platforms, from a typical government-base model to a European-base model with funding from Water JPI, Interreg and potentially the Horizon 2020 New Green Deal next year (see Stakeholder map for project details, Appendix 3). These research projects have a more community-orientated goal, as well as reinforcing research collaboration. Ireland and the UK are in a unique position to collaborate on peatland research and this has been initiated via the International Union for Conservation of Nature (IUCN) for example. While funding remains the main barrier for better coordinated peatland research environment, identifying stakeholders and associated funding platforms would help, for example sourcing alternative funding when research funding has finished.

☞ **R 1.28: Priority should be to widen the sources of funding in order to establish long-term monitoring,** which is typically lacking around restoration projects as funded research projects are always limited in time. In a similar vein, the lack of funding for researchers to train communities and practitioners is critical to enable transfer of skills, as well as efficiently communicating the science to the public. Finally, a new model of co-designed research that integrates citizen science must be developed to bring a bottom-up, place-based perspective to peatland research.

5.2.4 Mechanisms to support inclusive and collaborative governance and encourage bottom-up approaches to peatland management/conservation

Equity and social justice are increasingly a concern in decision-making on future land uses of peatlands (Bresnihan & Hesse, 2019). Assessment and valuation should be inclusive and transparent in considering a wide range of societal values, so that "the voices of those who benefit 'on the ground'" are heard (Jax et al, 2013, p. 264). People on the ground affect and are affected by ES both positively and negatively, so it is crucial to create pathways where the benefits and values can be communicated to policy makers to inform decision making (Jax et al, 2013). This can lead to better implementation and social acceptance of environmental policies and help to support arguments for conservation and restoration (Hirons et al, 2016). The use of deliberative and participatory processes such as those outlined in Section 3.2.3, provide a pathway to communicating such values. It has been shown that the *process* of decision making is as important as the outcome for the long-term sustainability of environmental management and conservation projects (Byg et al, 2017). Other mechanisms identified as important for engaging and empowering communities in conservation include meaningful engagement from the outset; implementing existing policies to build trust; a strong partnership approach; and platforms to support collaboration across sectors and scales (Crowley et al., 2020). The following recommendations can help to support sustainable management of peatlands at community level:

☞ **R 1.29: Build local community capacity in understanding, monitoring and assessment of peatlands through training, citizen science initiatives and knowledge exchange.** Such opportunities for knowledge sharing can also help agencies understand how policies and plans affect communities and how they can be better implemented and accepted at local levels.

☞ **R 1.30: Develop structures and supports for community groups applying for funding.** This could help community groups assess their readiness for making a funding application through assisting them to identify bridging finance, understand governance requirements, permissions for work in protected areas, and other funding conditions (e.g. workshops or webinars with funders similar to local authority 'pre-planning' clinics).

☞ **R 1.31: Develop strong partnerships between state agencies and community groups and networks in an open, transparent, two-way process of information sharing.** The Community Wetlands Forum provides a platform and advice for developing such partnerships and Public Participation Networks (PPN) could also be better utilised to provide guidance and funding to community environmental groups.

☞ **R 1.32: Encourage public sector organisations to have dedicated community liaison staff with expertise in community engagement and knowledge of participatory approaches to conservation.** This could help overcome institutional reluctance to share power with communities and ensure they have an equal voice as stakeholders.

☞ **R 1.33: Encourage action research approaches**, i.e. research that is initiated and driven by communities, and where **communities are involved with researchers** in all aspects of the research process. Action research is a collaborative and cyclical approach that aims to bring about mutual understanding, social change, and action (McNiff, 2014).

5.2.5 Integrated management

ES assessment and valuation have traditionally focused more on quantitative methods from economics and the natural sciences, since these disciplines underpin the ES approach, rather than on qualitative social science methodologies (Hirons et al, 2016).

☞ **R 1.34: The need for integrated rather than single-value approaches to ecosystem assessment and valuation, which combine ecological, cultural, economic, and ethical value dimensions, is increasingly advocated** (Díaz et al., 2020, Jacobs et al., 2016).

Such a new 'culture of valuation' should account for equity issues and requires interdisciplinarity, communication between different governance levels, and appropriate methods. All of these elements can be more costly in time and resources and thus are frequently overlooked or omitted (Jacobs et al, 2016). However, given the non-substitutable and often irreplaceable nature of many CES, it is crucial that resources are provided for their protection and enhancement.

5.3 Priority 2: Identify land use /land use change impacts and co-benefits of management options

The identification of the impacts of each land use / land use change and co-benefits of available peatland management options on ecosystem services (ES) is the first step in re-imagining their contribution to Ireland's future. Following the review presented earlier in this document, we provide here a coherent vision of the range of peatland utilisation and known (or yet unquantified) impacts on key ES, such as climate, biodiversity, water and socio-cultural (

Table 11).

Aim: to provide an accurate understanding and coherent vision of peatland utilisation, their impacts and the available choices.

- Embed each peatland management decision within an overview of peatland utilisation options, impacts and co-benefits

☞ **R 2.1**: It is recommended to identify and disseminate scientific facts about peatlands pertaining to each management decision in order to provide a coherent vision of the range and extent of peatland utilisation and known impacts on key ecosystem services, such as climate, biodiversity, water and socio-cultural (Table 5). While we have aimed to target specific land use and specific issues with the most appropriate potential mitigation measures, the guidance is not overly prescriptive, as each peatland site is different. Successful rewetting of degraded peatlands is a major challenge and, in some cases, may be a balancing act between biodiversity, climate and socio-economic benefits (Renou-Wilson et al., 2019, Renou-Wilson and Wilson, 2018). These must be site-specific based on informed consequences of the trade-offs.

Table 11: Peatland land use and land use change impacts on ecosystem services (ES). Icons represent positive, negative and no change.

Land use		Ecosystem Services				
From	To	Management action	Climate	Biodiversity	Socio-cultural	Water
Natural	Natural	➢ Full protection	👍	👍	👍	👍
	Industrial peat extraction	➢ Total vegetation removal ➢ Intensive drainage ➢ Removal of peat	👎	👎	👎	👎
	Domestic peat extraction	➢ Partial vegetation removal ➢ Indirect drainage ➢ Partial removal of peat	👎	👎	👍 👎	👎
	Grassland	➢ New vegetation cover ➢ Drainage ➢ Fertilisation	👎	👎	👍 👎	👎
	Forestry	➢ New vegetation cover ➢ Drainage ➢ Fertilisation	👎	👎	👍 👎	👎
Drained	Restored	➢ Drain blocking ➢ Rise in water level ➢ Plant re-introduction	👍	👍	👍	👍
	Rewetted only	➢ Water table management	👍	👍 👉	👍	👍
	Paludiculture (wet agriculture or forestry)	➢ Water table management ➢ Wet species	👍	👍	👍	👍
	Shallow drained grassland	➢ Water table management	👉	👉	👍	👉

5.4 Priority 3: Implement policy and ensure compliance with relevant regulations

5.4.1 International and national policy context

Global conventions, initiatives as well as European and national policies have implications for peatland management and uses of peat, either because their remits cover important global issues, of which peatlands form part of, or because they were established with very specific mandates, the achievement of which directly requires sustainable management of peatlands.

Ireland must provide a more coherent and effective implementation of the objectives of existing global and national policies, which not only provide awareness for policy-makers but also frameworks for national actions and international cooperation for the conservation and sustainable management of peatlands.

Peatlands have been increasingly recognised as very valuable ecosystems and are highly significant for the global efforts to combat biodiversity loss, climate change, as well as contributing to most of the United Nations Sustainable Development Goals (SDG) (Tanneberger et al., 2020). Key recent developments have included the 2019 UN Environment Assembly resolution on '"Conservation and Sustainable Management of Peatlands", which acknowledges the contribution of peatlands in the implementation of the 2030 Agenda for Sustainable development (UNEP, 2019). Further impetus is present in the United Nations Decade on Ecosystem Restoration (2021–2030).

The environmental damage caused by peatland drainage is at the core of key international environmental issues: GHG emissions, biodiversity loss, and water quality degradation. International biodiversity and climate change conventions (Convention on Biological Diversity and United Nation Framework Convention on Climate Change (UNFCCC)) now recognise peatlands as a priority for action, with peatland rewetting and restoration identified as "low hanging fruit" in mitigating global changes. At EU Level, wetlands have already been highlighted as playing a central role in achieving the temperature goals agreed in the Paris Agreement, and peatlands are already included in 2030 Climate and Energy Framework (European Parliament, 2018). At the national level, the Climate Action and Low Carbon Development Bill and Amendment (2020) has identified the establishment of legally binding GHG emissions targets (following EU targets) as a key priority to the transition to a low carbon economy. This could be achieved through a significant lowering of emissions, especially by improving the management of carbon-rich soils, such as peatlands, as expounded by the Climate Change Advisory Council in their Annual Review (2020): "*The rewetting of drained peatlands is one of the most cost-effective measures supported by carbon tax revenue*". This has been re-affirmed in the European Green Deal with new Common Agriculture Policy instruments (CAP 2021–2027) to be implemented to decrease GHG emissions associated with managed peatlands (European Parliament, 2020). In addition to decarbonising economies, offsetting emissions in sectors that are difficult to abate (aviation) has been targeted with international schemes involving peatland restoration (ICAO, 2016).

There is now also widespread evidence that drained/mined peatlands can negatively affect the delivery of water related ES (Bonn et al., 2016, Renou-Wilson et al., 2011). Drained peatlands increase natural organic matter in receiving water which can be very problematic for potable water, making treatment more challenging and more costly. Ireland must find solutions that not only satisfy international commitments with regards to EU water-related Directives but also address climate change and sustainability demands.

5.4.2 Comply with existing regulations and associated schemes

The case for the sustainable integrated management of peatlands is underpinned by existing legislation whose compliance directly bears on the development and outcome of the sustainable management of peatlands.

Compliance with existing regulations with the eradication of deficiencies or conflicts in these legislations must be improved as a first approach to integrated peatland management in Ireland.

5.4.2.1 Conservation/biodiversity governance

In broad terms, the objectives of the Habitats Directive are to contribute towards the conservation of biodiversity by requiring Member States to take measures that (1) maintain or (2) restore the natural habitats and wild species listed on the Annexes of the Directive at a favourable conservation status. Following the latest report on the assessment of the status of habitats (NPWS, 2019), the habitats of most pressing concern include all types of peatlands. While raised bogs have been the source of specific restoration schemes, blanket bog Special Areas of Conservation (SAC) continue to dry out and lose their active peat-forming areas, due to direct and indirect impact of sheep grazing, turf-cutting and forestry. Furthermore, an end to turf cutting alone will not restore the ES of the bogs. Thus, the first priorities are thus:

☞ **R 3.3: To urgently meet the objectives for designated protected peatlands under the Habitats Directive and restore all raised and blanket bogs SAC.**

Studies funded by EPA and NPWS have projected that each hectare of restored active raised bog could sequester c. 1.85 t CO_2 ha^{-1} yr^{-1}, with a concomitant reduction of 6 t CO_2 ha^{-1} yr^{-1} if this active bog is restored from a very degraded condition. However due to variability in site conditions, significant management works and management are required to reach the maximum GHG reduction and potential C sequestration across the full spectrum of designated sites (c. 27,000 ha). Prioritising the least degraded (to bring back C sequestration function) and the worse degraded (to decrease the negative services in the form of C emissions) is critical to optimise the benefits from such management. In addition, it has been shown that this must be achieved as soon as possible to ensure that a sufficient range of natural/rewetted peatlands are properly managed to maintained the necessary water levels to sustain as many ES as possible in the wake of climate change (Renou-Wilson and Wilson, 2018). Less than 50,000 ha of raised bog is restored or scheduled for restoration works, equating to less than 25% of the protected raised bogs. For blanket bogs, the situation is more dire with less than 15,000 ha of blanket bog restored or scheduled for restoration works, equating to less than 4% of the resource.

☞ **R 3.4: Providing sufficient recurrent funding** is thus paramount to ensure full implementation of these regulations through the relevant national authorities as well as focussing on improving the measures that were not sufficient to meet the objectives of the Habitats Directive. This means that funding should include long-term monitoring, which is not currently supported by funding platforms, such as the LIFE projects. Thus, **new funding mechanisms** for peatland restoration schemes are required, which should include long-term monitoring (post-LIFE or other short term research projects). In addition, LIFE projects have solely focussed on or around designated sites (SACs and SPAs) which is less than 20% of the peatland resource. The remit must be expanded to include case-studies that demonstrate/showcase best practice for restoration/rewetting outside designated sites. Furthermore, it has been widely acknowledged that such schemes require the support from the communities located around the bogs and thus funding support should be **enhanced for local communities**. In addition to peatland community schemes, **incentives to promote citizen science** involvements could be an efficient means to help with the long-term monitoring around the Natura 2000 network.

5.4.2.2 Environmental governance

In order to aim for a sustainable management of peatlands, drainage-based utilisation can only form an exception, which must be subject to planning regime and licensing. This is after the squashing of the Peat Extraction regulations (S.I. No 4 & No 12 of 2019), whereby peat extraction was solely regulated by the EPA and exempt of the planning process. The EPA IPC Regulations (S.I. No 283 of 2013) is the main instrument regulating pollutant emissions from industrial installations. Specifically, in the context of peat extraction, the EPA are required to ensure that an Environmental Impact Assessment (EIA) and Appropriate Assessment (AA) have been carried out as part of the associated planning application prior to the issue of an Integrated Pollution Control (IPC) licence (in excess of 30 ha regardless of other peat extraction areas). There is still no progress on the development of a separate regulatory regime that will bring smaller-scale commercial peat extraction (on lands of less than 30 ha) under a new local authority licensing system, incorporating EIA and AA, as required, and enforcement powers.

Bord na Móna (currently the only industry under IPC licensing regime) and other peat companies (with licencing applications on-hold pending judicial review) have all acknowledged 'water pollution' as the most significant risk from their operations and a review of their IPC applications (www.epa.ie) shows that clear scientifically-based mitigation measures that would protect adjacent water courses are missing, while in-house ad-hoc protocols are deployed. The extent and status of implementation of mitigation measures in the peat extraction sector have never been appraised. While research is ongoing (www.ucd.ie/SWAMP), it is critical that the potential impacts of all activities involving the drainage of peatlands are correctly appraised and proven mitigation measures applied appropriately together with scientifically robust rehabilitation plans. New guidance on the process of preparing rehabilitation plans (EPA, 2020a) have been developed in the context of the IPC licencing of peat extraction activities, to remove any imminent environmental liabilities. These are limited, however, and form only a stepping stone for future rewetting works that would bring back ES.

☞ **R 3.5: Finalising the legal status of all peat extraction activities is urgently required together with the implementation of evidence-based mitigation measures.**

Enhanced Rehabilitation Bord na Móna Scheme (DECC, 2020a)

Following the announcement in Dec 2020 of €108 million in funding from the Just Transition Fund, Bord na Móna aims to carry out enhanced rehabilitation works on 32,500 ha of their cutaway peatlands currently used for fuel energy production. This not a 'restoration' scheme since the raised bogs that existed prior Bord na Móna's mining activities will never be restored to its original shape having lost most of their peat. Bord na Móna must go beyond the existing IPC licencing 'rehabilitation' requirements (EPA, 2020a), with 'enhanced' rehabilitation plans covering managed rewetting through bunding, drain blocking and water management, as well as other techniques to facilitate the reintroduction of vegetation such as *Sphagnum* inoculation. Water quality and return of aquatic biota are being monitored on some of these enhanced sites as part of the SWAMP project (www.ucd.ie/SWAMP). However, it is critical that transparent monitoring of key performance indicators (whole ecosystem as well as terrestrial and aquatic biodiversity) is carried out to support the actions under this scheme. Such schemes would be wasted if it didn't inform further management of peatlands nationwide. This is in effect affecting less than 3 % of our peat soils resources but could inform potentially 100 times this area of drained and degraded cutover bogs.

It should be clarified that, as reported in the DECC press-release, the carbon stored in Bord na Móna's remaining landholding was over-estimated. The EPA funded AUGER project estimated only 50 million tonnes of carbon stored (that is if properly rewetted), instead of 100 million tonnes of carbon). They have also over-estimated the potential to sequester 3.2 million tonnes of carbon out to 2050: using sequestration rate seen in drained-only, rewetted bogs, -0.49 t C /ha, 32,500 ha over 30 years would sequester only 0.5 million tonnes of carbon (Renou-Wilson et al., 2021).

5.4.2.3 Agricultural and forestry governance

The most recent analysis indicates that approximately 6% of the country or 420,000 ha is composed of 'agricultural' peats across a wide range of farming intensities, though predominately low intensity farming (Green, 2020). Nutrient rich peat soils reclaimed for improved grassland and which are mostly located in the Midlands, are known hotspots of GHG and fluvial carbon emissions (Renou-Wilson et al., 2014). Reduced management intensity (raising and managing the water table accordingly throughout the year) would significantly limit oxidation and emissions of CO_2 and N_2O. The Teagasc Marginal Abatement Cost Curve estimates that each rewetted hectare would reduce emissions by 11 tonnes CO_2, although this would require raising the water level to near the surface, and active management will be required to maintain it at this level. Savings of 6 tonnes CO_2/ha/year can be achieved if the water level is kept within 20 cm below the surface (Renou-Wilson et al., 2016). Action 15 of the Ag Climatise report sets a target to implement reduced management intensity on at least 40,000 ha of drained agricultural organic soils (DAFM, 2020). This has been recognised as critical in order to avail of the credit of 26.8 Mt afforded by the EU (for LULUCF when calculating Ireland's share of EU GHG emissions reductions in the period to 2030). However, such target represents less than 10% of all drained organic soils used for agriculture and the details in the report are vague as to how agricultural peats that are suitable for water table management should be identified and prioritised to reduce GHG emissions. As discussed above, the focus should be:

☞ **R 3.6: Rewetting of nutrient rich organic soils that act as hot spots of both CO_2 and N_2O should be prioritised.**

No detailed costings have been undertaken by DAFM or Teagasc on the rewetting of agricultural peat soils. A range can be determined using the lower estimates (€400 ha^{-1}) incurred on Bord na Mona's rewetting of cutaway/cutover bogs where the cost is low due to the scale of operations, existing conditions, ownership etc.. At the higher end of estimated rewetting costs, studies in Germany have shown that €10,000 ha^{-1} may be required but this is where land is converted for paludiculture (Renou-Wilson and Wilson, 2018).

☞ **R 3.7: Incentives are required to rewet agricultural peat soils,** and this has already been successfully acknowledged in pilot schemes where the support levels are similar to those under GLAS actions paid to farmers to specifically protect endangered species under the European Innovation Partnership (EIP), for example:

(1) The Hen Harrier EIP project, which includes peat soils rewetting and management of cattle on peaty hills as one of their cost-effective actions (http://www.henharrierproject.ie/).

(2) The Freshwater Pearl Mussel EIP project, which demonstrated the sustainable management techniques and practices on their bogs to local farmers and forest-owners in two freshwater pearl catchments (https://www.pearlmusselproject.ie/).

While reduced management intensity could be funded within a reconfigured GLAS or equivalent scheme in the future, it is critical that payments are covered over a long-term or indefinite period of time. This is very much in line with the next CAP submission and proposed tools.

In this vision, the new DAFM pilot-scheme planned for 2021 under the EIP initiative model (agriculture.gov.ie call under the Rural development Programme 2014–2020) will serve as "proof of concept" for scaling up to larger agri-environmental schemes and provide estimates on currently missing cost and benefits of rewetting agricultural peat soils. Of importance here is to consider the range of sustainable options available to the farmers. Wet peatlands release less CO_2, can potentially sequester carbon, help improve water quality, provide habitats for rare and threatened biodiversity, and can still be used for production of biomass. This could range from "**wet wilderness**" (the absence of biomass harvesting and other on-site management with the focus on the provision of regulating services and wilderness biodiversity values) to "**paludiculture**" (wet cultivation); the latter being either **low-intensity** (with regular harvest from spontaneously established vegetation for biomass use (i.e., permanent grassland paludiculture with sedges or grasses under light grazing) or **high-intensity** (the cultivation of deliberately established, selected wetland crops under intensive management with the goal to produce the highest quantity and/or quality of targeted biomass (i.e. cropping paludiculture with cattail (*Typha* spp.), sphagnum or sundew (*Drosera* spp.) for medicinal purposes). Current research projects are trialling methods for possible paludiculture on cutover and cutaway peatlands in Ireland as well as investigating the viability of the enterprise (Carepeat; CarbonConnects).

Several countries have already highlighted at CAP negotiations the objectionable inconsistency that deeply drained peatlands used for conventional agriculture release ≈29 t CO_2eq per hectare/year and are currently fully eligible for CAP payments. However, rewetted peatland used for paludiculture that release 0–7 t CO2eq per hectare/year, are currently not eligible for CAP payments (Tanneberger et al., 2020). This is something that is now being lobbied by several stakeholders as CAP is a key source of funding for supports for farming communities.

☞ **R 3.8: Ireland must look at the combination of new CAP instruments that are now available, which could pave the way toward low-emission peatland utilisation to satisfy the need of a range of stakeholders.**

Most recent Forestry Regulations (SI No. 191 of 2017) require an environmental impact assessment to be carried out in respect of an application for a licence for affectation (>50 hectares) and must give regard to the use of natural resources, in particular land, soil, water and biodiversity; and the location acknowledging the environmental sensitive especially of 'wetlands', riparian areas and rivers. Afforestation on peatlands has largely ceased and afforestation grants currently exclude unmodified raised bogs, infertile blanket and midland raised boogs, designated blanket and raised bogs, albeit grants are still available for organic soils <50 cm. Key findings from forest stakeholders consultations highlight that forests on blanket bog produce poor timber quality and results in a net cost; environmental NGOs have a preference for natural blanket bog and native woodland; and eutrophication and siltation arising from forest activities on blanket peat have direct impacts on FPMs and salmonids (Juerges and Krott, 2017). Continuation of peatland forestry via reforestation, for some sites is deemed incompatible with conservation objectives for designated bog habitats. Similarly, restoration to 'high' status for FPM under Water Framework Directive may not be compatible with reforestation. In these circumstances, permanent forest removal may be considered by the Forest Service accompanied by a management plan for future land use (DAFM, 2018).

Coillte is engaged with habitat restoration and has completed active restoration on 571 hectares of raised bog at 14 midland sites within SACs. Approximately 2000 hectares of blanket bog has been restored through draining blocking and rewetting. Where reforestation does occur 'reforestation objectives' are sought for clarification on the intention of the forest owner in relation to subsequent rotations, i.e. alternative approaches such as broadleaf, mixed forest, continuous cover forestry, reforestation for biodiversity and water protection (DAFM, 2018)

Minister Hackett has announced in December 2020 the funding for a project similar to the LIFE project on the Western Peatlands focusing on their restoration and management for environmental benefits (https://www.coillte.ie/coillte-nature/ourprojects/wildwesternpeatlands/).

☞ **R 3.9:** Much evidence points to the unsustainability of afforested peatlands and **decisions on future land use must be site specific accounting for the full suite of ES and a clear regard for**

sensitive receptors, i.e. ecological status of downstream waterbodies, drinking water protected area and protected habitats and species.

5.4.2.4 Water governance

The River Basin Management Plan for Ireland 2018–2020 (Government of Ireland, 2018) reports that "Of the 119 river water bodies that are at risk because of activities taking place within peatlands, 46 (39%) of them are in areas that have peatlands owned by Bord na Móna, which has 87 peatlands in these areas. The remaining 73 water bodies are at risk from other activities, such as domestic turf extraction, unauthorised peat extraction, windfarm construction, forestry or other commercial peat activities."

In order to achieve the objectives of the Water Framework Directive (WFD) of achieving at least good status on all waterbodies and achieve compliance with the requirements for designated European sites (SAC and SPA), effective, resilient and multi-level governance structures must be developed and integrated across policy domains. In Ireland, the implementations of the various Water Policy Regulations (SI 722 of 2003; Surface Water Regulations: SI 272 of 2009; Drinking Water Regulations: SI 122 of 2014) and together with the latest 2018-2021 River Basin Management Plans (RBMP), the National Catchment Flood Risk Assessment and Management (CFRAM) Programmes but also the Freshwater Pearl Mussel Regulations (2009) and associated sub-basin management plans, should provide an excellent foundation from which to build an integrated mechanism as exemplified in the OECD principles on water governance (OECD, 2015).

Of importance here is the specific evidence-based priorities in the RBM Plan 2018–2021 and principal actions related to peatlands for the 2nd cycle (Government of Ireland, 2018), namely:

(1) To ensure full compliance with relevant legislation (new planning regime for peat extraction) and targets set out in the National Peatland Strategy. In its 'Actions', it is specifically stated "A25: For all peatland related activities, it should be demonstrated that they do not, either individually or in-combination with other activities, adversely impact on the environmental objectives of the WDF, associated daughter Directives and national regulations." With the context of the designated sties, Action 26 states "Peatland related activities should not significantly alter the environmental supporting conditions for designated habitats" with water quality being the major risk for which the conditions are not met.

(2) The rehabilitation of Bord na Móna bogs and the implementation of its Sustainability 2010 Strategy and Biodiversity Action Plan 2016–21.

(3) Support to investigate the issue of peat extraction and ammonia emissions and the need to evaluate mitigation measures for improving water quality from drained peatlands. This is not only critical for the new applications for continued peat extraction for horticulture by other private companies but also to be considered within the framework of the new Guidance on Rehabilitation plans (EPA, 2020a). It is hoped that the outputs of the SWAMP project (www.ucd.ie/swamp) will inform the next (3rd) cycle of RBMP (2022–27) with a proposed workshop to identify the significant draft conclusions.

☞ R 3.10: It is recommended that peatland degradation status is fully recognised in the RBM plans and thus monitored carefully in all catchments, especially with regards to DOC and ammonia emissions within each catchment.

Drinking Water quality standards are well regulated but compliance of treated water is not sufficient to prevent further water quality decline. Raw water monitoring of precursors allows for estimations of loadings of organic matter, providing water managers with visibility on trends and links the contaminant to stakeholders / land users in the catchment (O'Driscoll et al., 2018b). UK water companies have investigated potential for catchment interventions in order to improve raw water quality at source and it is acknowledged that catchment management could make a contribution to mitigating recent organic matter in some circumstances, i.e. forested peat, uniform wide scale application is not recommended (Williamson et al., 2020). Rather, it is proposed that site specific interventions are selected with key factors, scale, effect size and duration of the catchment intervention considered crucial. Some interventions that have been trialled include ditch blocking, re-vegetation of bare peat, deforestation and managed burning. Thus far in Ireland interventions are very much considered for treated drinking water only with a nod to source protection (https://www.hse.ie/eng/health/hl/water/drinkingwater/trihalomethanes-in-drinking-water-position-statement.pdf). The WHO Water Safety Plan approach to ensuring drinking water is both safe and secure puts much emphasis on the 'source' component of 'source – to – tap' (WHO, 2009) a component which has very much been picked up on in the NFGWSs 'A framework for drinking water source protection'.

5.5 Priority 4: Identify gaps in knowledge- invest in collaborative research, monitoring and innovation

5.5.1 Environmental and land use research

The long term social and economic outputs of environmental and land use research are well known but lack support. Funding support mechanisms for environmental and land use research in particular, has seen an erosion in national science funding platforms (e.g. SFI), to the unfair advantage of 'added value' short-term research that delivers direct economic benefits. This is a false economy as a healthy environment underpins all sustainable economic development. This requires long-term research framework to allow for the observations of natural processes.

More specifically, the sustainable management of peatlands and associated benefits relies primarily on a robust scientific evidence base, which has been consistently pointed out (Climate Change Advisory Council, 2020, NPWS, 2015b). While the EPA and NPWS have been the major funding platforms of peatland research in the past 15 years, DAFM and Teagasc have initiated research for 2021, which should be greatly expanded given the next CAP funding developments. Land use research is critical to the sustainable management of our land as peatlands are at the cross-roads between so many individual or mixed land uses. The spatio-temporal linkages associated with the impact of peatland utilisation are complex and go beyond simple indicators to affect a range of ecosystem services. An ecosystem approach has been proposed as a useful tool to assess properly the environmental impact of various management options (e.g. windfarms on peatlands by Wawrzyczek et al., 2018).

☞ **R 4.2: Thus, key research questions pertaining to land use and land use change affecting peatlands including windfarm, forestry and agriculture are to be carefully scoped out compiled and prioritised.**

Despite the breadth of research funding over the last decade or so, significant information gaps still exist, particularly in blanket bogs degraded by domestic peat extraction despite being one of the largest peatland land use categories in the country. The direct and indirect impacts of management actions/interventions and especially rewetting and restoration typically work in synergy across various parts of the ecosystems (soil, atmosphere, biota), which are rarely assessed in combination (e.g. NEROS project). For example, when the restoration of a peatland may impact adjacent freshwater rivers inhabited by key species, such as freshwater pearl mussel. The assessment of these indirect impacts is rarely taken into consideration, especially in terms of the economic implications of restoration works.

☞ **R 4.3: An ecosystem approach (used to improve ecological impact assessment) should be called upon to set up the next research priorities surrounding peatlands.**

5.5.2 Long-term monitoring and datasets repository

Long-term datasets (monitoring prior, during and after an intervention) are critical in understanding the impacts of peatland management and further provide feedback to further guidance. Few published studies include baseline monitoring, and even fewer include long-term post-restoration monitoring. The vast majority of restoration projects fail to identify adequate targets and thus provide evidence-based data for future actions. Existing LIFE funded projects in particular were a missed opportunity to gather a range of data prior to restoration/rewetting, at regular intervals after restoration, as well as reference sites (missing in most cases). The data is not sufficiently comprehensive to allow statistical analyses and comparisons. Cessation of funding means that research capacity is also wasted.

☞ R 4.4: Tracking the success of interventions for integrated peatland management (e.g. long term monitoring of key performance indicators following rewetting schemes) is critical to develop a robust guidance.

There is a lack of repository of research datasets that could further inform integrated peatland management. Of particular interest given recent events involving windfarm on peatlands, there exists a large dataset collected around planning conditions of projects on peatlands which should be collected and critically analysed to further inform evidence-base guidelines for similar projects.

Similarly, low intervention restoration techniques supported by local groups or small-scale funded projects (LAWPRO) may be very successful in re-orienting undesired trajectories of degraded bogs and contribute to the return of beneficial services. Scoping out these projects and collecting the relevant data (either governmental, research or citizen science) is another action to better inform the guidance.

☞ R 4.5: As a priority, Ireland lacks a compendium of restoration/rewetting projects and peatland datasets available to all stakeholders.

Finally, the research community must also better collaborate (e.g. existing EPA study sites across various projects) as well as reach out to stakeholders, and to communities especially, in order to have synergy across projects and harmonise methods to compare datasets

Additional sources of research funding have been identified at various local institutional levels (e.g. LAWPRO, An Fóram Uisce), which can help fulfil the long-term monitoring needs, as well as pilot studies. This resource may not be just monetary but also simply advisory. NPWS and other funding research institutions must lead the way for long-term scientific research on peatland ecosystems with additional budget for researchers to be trained to communicate and to also train communities: see for example the IUCN “Eyes on the bog” which provides a scientifically robust, repeatable, low tech, long-term monitoring of peatlands initiative (IUCN, 2020).

☞ R 4.6: Development a standardised methodology and training capacity that enables individual peatland sites to be consistently monitored and thus creating a network of comparable sites.

☞ **R 4.7: Establish a national peatland observatory / research site network to support long-term research and initiate large scale pilot studies/catchment interventions; along with a common research protocol (definition, measurements etc.).**

5.5.3 Innovative sustainable management options

While several innovative after-use of cutaways have been initiated by Bord na Móna with business opportunities (e.g. aquaculture, organic medicinal plant), one potentially feasible large-scale option for all landowners is 'paludiculture'. Paludiculture (latin 'palus' = swamp) means the productive utilisation of rewetted peatlands. It has been demonstrated that such land use can (1) help our climate and environment, (2) produce renewable resources without competing with food production, and (3) contribute to the development of rural areas (University of Greifswald, 2012). Paludiculture is an emerging, promising alternative to the industrial drainage-based land-use of peatlands, centring on the harvesting of biomass on wet peatlands. Various options of land use of wet or re-wetted peatlands have been tested globally. It is often associated with new utilisation schemes (e.g. reed cutting for insulation boards in Germany), or indirect environmental measures (e.g. cattail soaks up nutrients before they enter waterways in Canada), or can provide innovative products (e.g. bio-fuel briquettes in Belarus). While initial trials at Kilberry Bord na Móna's cutaway bog demonstrated the difficulties with managing the water table, scientific research with pilot scale studies on private land must be initiated. While sphagnum farming could potentially yield a 'green product', the action of rewetting degraded peatlands for biomass production could also bring additional benefits in terms of CO_2 emissions reductions, water storage/flood control, water purification, erosion control and biodiversity. These additional ES are increasingly becoming commodities on the markets (Bonn et al., 2014). The overall economical perspective of such a transition from drained land-use to rewetted land use of industrial peatlands has yet to be fully appraised. One such trial will be commenced at All Saints Bogs in 2021 (Carepeat project).

☞ **R 4.8: R 4.7: New, well-designed experimental field studies with replications should be established at various cutaway and cutover bogs across the country with suitable varied environmental characteristics, in order to trial wet cultivation techniques (paludiculture).** Such an experiment should aim first to identify the most appropriate Sphagnum and other plant species for a sustainable farming production system, given the type of degraded bogs available, and the regional climate. In combination with the scientific evidence, a socio-economic analysis around alternative income streams on rewetted or marginal organic soils should be carried out.

5.6 Identify Resources

5.6.1 Existing funding platforms

Following the extent of benefits reviewed here, financing integrated sustainable peatland management should be a long-term policy. The priority lies with the blanket bog SAC/SPAs, as well as the remaining raised bog SACs that have not been restored to date. The costs of measures, such as those detailed here, is difficult to calculate with precision. NPWS suggests a potential once off cost of €2,000 per ha, based on its current Irish Raised Bog LIFE project, to restore protected raised bogs. This would cover restoration works, resources, once-off compensation costs and voluntary land purchases. Put another way, the cost of not restoring the network of protected raised and blanket bogs can be alternatively considered via proxies, such as the amount CO_2 emitted (~ 4-6 million tonnes of CO_2eq each year), the cost of cleaning pollutants from surface and drinking water, the cost of lost biodiversity etc. Governmental support to provide funding under the Habitats Directive regulations is unequivocal and perpetual. There is need for government bodies to carry out a full economic analysis of these requirements. Such economic analysis is key priority to get a coherent vision of how and why Irish peatland resource should be managed in such integrated fashion.

Yet, there are approximately 1 million ha of non-designated degraded peatlands in Ireland. Thus, as a second stream of resources to finance the sustainable management of peatlands, we have identified results-based agricultural payment schemes as a critical instrument to set attractive incentives for reducing GHG emissions and for supplying other ES (e.g., nutrient retention, water quality, and flood regulation). It is critical that those pilot schemes attract as many landowners as possible from the widespread geographical area where peatlands occur. LAWPRO, Teagasc and the An Fóram Uisce have a role to play here in not only informing the relevant stakeholders but also in the long-term monitoring. Thus, staff and funding within these institutions should be identified not only for direct involvements in projects but also as advisory capacity.

As peatlands are rarely in single-ownership, integrated management of peatlands require special attention extended to communities living around the bogs. While national funding opportunities are available for communities (as described in Bullock and Flood (2020), it is critical that the government provide a long-term financial framework to secure the continuity of the sustainable management of shared peatland resources. Existing peatland community schemes (DAHG) have been unbalanced towards communities in the Midlands. This must be rectified with support to communities living around bogs (not just the designated ones) in the west of Ireland and who have strong economic (tourism) and cultural incentives to manage their peatland resource.

5.6.2 New funding mechanisms

While a number of large EU and state funded projects are on-going and due to start in 2021, vast areas of peatlands require financial intervention from other sources. Remunerating ES, especially carbon credit schemes must be developed. Such a scheme would provide a mechanism by which businesses, organisations and individuals could invest in land-management and restoration schemes that would deliver GHG reductions or removals, delivering financial support to farmers and others to adopt sustainable land-management practices, undertake restoration and increase the extent of ecologically valuable habitats. There is an increasing awareness that multinational corporations are seeking to invest in restoration projects for GHG offsetting and water resources purposes. Peatland restoration has been targeted for such offsetting schemes in sectors that are difficult to abate (e.g. aviation) (ICAO, 2016). The first carbon credits from peatland rewetting have been sold in 2011 (from the German regional Moorfutures 2.0 scheme), followed in 2017 by the UK Peatland Code and the Netherlands in 2020. A methodology for rewetting drained temperate peatlands has been launched under the Verified Carbon Standard. There is no such mechanism to facilitate this in Ireland despite the existing scientific evidence base that is required to allow the GHG emission savings associated with proposed intervention measures to be quantified and demonstrated. While further data is required for certain land use and geographical regions to support such a scheme, an initial assessment of maximum carbon offset potential from Irish peatlands should be established. A case study for the Falkland Islands gave an example of how to carry out such an assessment and review the advantages and disadvantages of various options of international schemes (Evans et al., 2020). It is predicted that carbon offsetting schemes would not only have the potential to deliver significant climate change mitigation, but would also support habitat conservation, provide cleaner water, and generate new sources of income for farmers/ landowners.

General Conclusion

This scoping report has focused on integrating and synthesising the scientific information needed to provide recommendations for management of Irish peatlands to optimise water quality, alongside co-benefits for other ecosystem services. It highlights the extent of damage to Irish peatlands and the knock-on impacts to other aspects of the environment, including water quality, carbon cycling and biodiversity. In addition, a thorough review of cultural ecosystem services has enabled evidence gaps to be identified, and guidance is provided on how best to elicit, assess, and include the wide range of values and perspectives for sustainable peatland management and decision making.

Current and alternative management options for different peatland uses (extraction, forestry and agriculture) are reviewed in terms of effectiveness based on best available knowledge, and knowledge gaps are highlighted. Given the degraded status of most Irish peatlands, the rewetting (first step in a range of management options ranging from wet cultivation to full restoration of peatlands) is the only management option that can deliver the full suite of ecosystem services associated with healthy peatlands (Figure 11).

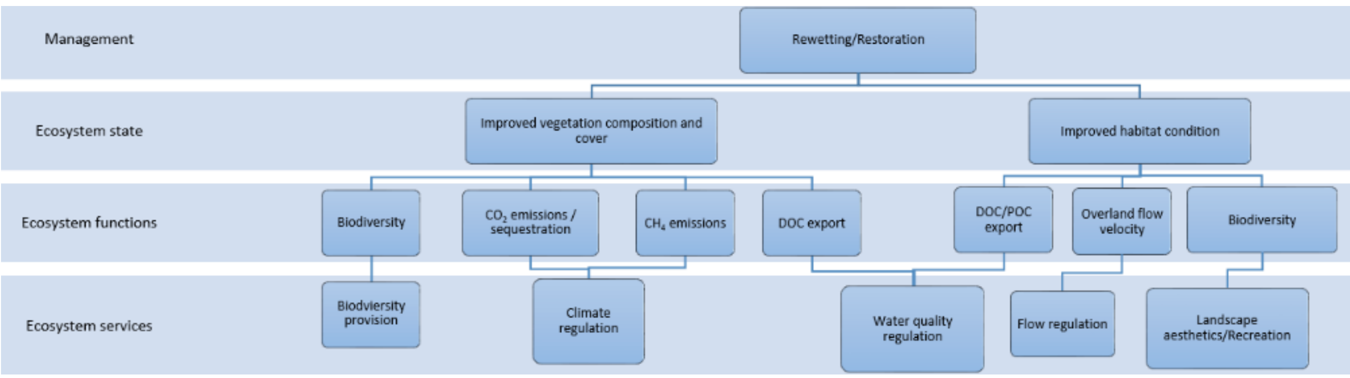


Figure 11: Schematic of impact of rewetting/restoration of a peatland on its states, ecosystem functions and ecosystem services.

Based on this scoping review, four evidence-based key priority areas have been identified, in order to meet the aim of optimizing water quality returns from peatland management while delivering co-benefits for climate and biodiversity. Within these priorities, solutions have been provided where possible, such as a stakeholder engagement map to aid collaboration, or key actions have been suggested as part of a strategic guidance framework.

These recommendations should be used to enhance future peatland management in Ireland in order to optimise water quality, while delivering co-benefits for biodiversity and climate change mitigation.

Glossary

Biodiversity: Refers to the diversity of all living things at genetic, species and ecosystem levels.

Catchment/catchment area: 1. An area from which surface run-off is carried away by a single drainage system. 2. The area of land bounded by watersheds draining into a river, basin or reservoir.

Constructed wetland: An artificial wetland constructed to treat wastewater. Specially selected plants and substrate provide an optimum environment for biological water purification and reoxygenation.

Cutaway peatland (industrial): A peatland where peat is being/has been extracted by industrial means. Peat extraction is the term used in this report to refer to peat production, peat mining or peat extraction. (Peat production is the term widely used in Ireland within the industry and is defined as the overall management or the processes and methods used to produce peat for commercial operations.)

Cutover peatland: A peatland where peat is being/has been removed through turf cutting by hand or small-scale mechanical peat extraction. Cutover areas are usually made of a mosaic of cut areas, face banks, pools, drainage ditches, uncut areas, scrubs, grassland.

Dissolved organic carbon (DOC): Organic carbon less than 0.45 µm in size (meaning it is dissolved in solution). DOC is largely the product of biological processes (such as release of plant exudates or through decomposition of polymeric particulate organic material). High molecular weight, coloured DOC of an aromatic and refractory nature entering waters can increase water colour and lead to 'brownification'.

Disturbance: A discrete event, either natural or human induced, which causes a change in the existing condition of an ecological system.

Ecosystem services: Fundamental life-support services upon which human civilisation depends. Examples of direct ecosystem services are pollination, provision of wood, and erosion prevention. Indirect services could be considered climate moderation, nutrient cycling, and detoxifying natural substances. The services and goods that an ecosystem provide are often undervalued as many of them are without market value.

Cultural ecosystem services: Cultural services are regarded as the environmental settings, locations or situations that give rise to changes in the physical or mental states of people, where the character of those settings is dependent on living processes; they can involve individual species, habitats and whole ecosystems.

Eutrophication: over-enrichment of minerals and nutrients in a body of water, leading to excess algae growth and depletion of dissolved oxygen.

Hydraulic retention time: The average amount of time that a soluble compound remains in a water body.

Local people: Any individuals or groups of people in an area who are affected directly or indirectly by peatland management decisions.

Minerotrophic: fed primarily from streams or springs and therefore supplied with dissolved minerals.

Mitigation: Technological change and substitution that reduces resource inputs and emissions per unit of output. Although several social, economic and technological policies would produce an emission reduction, with respect to climate change, mitigation denotes the implementation of policies to reduce greenhouse gas emissions and enhance carbon sinks (IPCC, 2007).

Peatland: A geographical area (with or without vegetation) where peat soil occurs naturally. For mapping purposes, a peatland should cover a minimum spatial extent of 1 ha.

> Active peatlands or mires: Peatlands on which peat is currently forming and accumulating. All active peatlands (mires) are peatlands but peatlands that are no longer accumulating peat would no longer be considered mires.
>
> Intact, pristine, natural peatlands: The terms 'virgin', 'pristine' and 'intact' have been used in several studies in relation to sites that look unmodified, uncut (as visible to the eye) and where no obvious factor is currently degrading the peatland. These terms are best avoided for use of habitat description such as peatlands in an Irish context. Most Irish peatlands are 'humanised' landscapes that have evolved, indeed sometimes originated, in close association with land-use systems. It would be impossible to find an Irish peatland that has never been grazed or used in some way by humans (e.g. burning).
>
> Near-natural peatlands: In this report, the terms 'near-intact' and 'natural' peatlands are interchangeable and are used to refer to peatlands that are hydrologically and ecologically intact, i.e. in which the eco-hydrology, in the recent past, has not been visibly affected by human activity and therefore includes active or peat-forming areas or is in the process of

regenerating such a habitat. A natural peatland thus requires a combination of components to be present in order to carry out all the functions and ecosystem services usually attributed to such ecosystems. As there are no completely undamaged peatlands left in Ireland, the most natural peatlands in the country are referred to as 'near-natural, but undamaged global peatlands are referred to a 'natural'.

Degraded peatlands: management or other external influences (such as climate change or deposition of acidifying pollutants) have caused changes to the peatland, including hydrological, ecological and structural changes. As a result, functioning and ecosystem services provided no longer resemble that of an intact, functioning peatland ecosystem, and disservices may instead take place, such as pollution of inland waters or release of greenhouse gas emissions.

Rehabilitation: Occurs where a site has previously been extracted (industrially) and involves allowing natural recolonization of vegetation in order to stabilise the bare peat surface and minimise pollution to air and water, as required by EPA Integrated Pollution Control (IPC) licencing and associated BATNEEC Guidance Note (1996).

Enhanced rehabilitation: A combination of engineering measures, ecology works, and natural recolonization aimed at rewetting degraded peatlands and returning them to species-diverse, active peatlands.

Restoration: Restoration involves restoring abiotic and biotic conditions close to the original state, including the hydrological regime and surface topography followed by the reintroduction of peatland flora such as Sphagnum. The effects of restoration are not immediate but rather involves management, which sets degraded ecosystems onto a positive trajectory for which benefits are not seen for many years.

Rewetting: The deliberate action of raising the water table on drained soils to re-establish water saturated conditions, e.g. by blocking drainage ditches or disabling pumping facilities. Rewetting can have several objectives, such as wetland restoration or allowing other management practices on saturated organic soils such as paludiculture (IPCC, 2014).

Peatland management: Management of peatlands involving human activities relating to peatland utilisation and land use.

Sustainable peatland management: management of peatlands that maintains their function as carbon sinks (by promoting carbon storage and sequestration), biodiverse ecosystems, and watershed maintenance. Some sustainable management options include re-wetting and avoiding drainage.

Particulate organic carbon (POC): Organic carbon particles between 0.45 and 1000 µm in size and suspended in the water column. POC includes partially decomposed organic material and is readily decomposable.

Peatland utilisation: Peatland management creates specific anthropogenic uses of peatlands. Examples include peat extraction, forestry and agriculture.

Social values: The types of values held in social situations or processes, including the values of particular communities or the cultural values of society at large. Social values can relate to education, well-being, biodiversity, history and heritage, spirituality, aesthetics, and recreation. Deliberative and non-monetary methods of valuation are often required to articulate the social values of cultural ecosystem services.

Stakeholders: People/organisations who seek to deliver a common goal of managing peatlands sustainably.

Acronyms

BMP: Best Management Practices

CCF: Continuous cover forestry

CES: Cultural ecosystem services

CH_4: Methane

CICES: Common International Classification of Ecosystem Services

CO_2: Carbon dioxide

DIC: Dissolved inorganic carbon

DNRA: Dissimilatory nitrate reduction to ammonium

DOC: Dissolved organic carbon

DWD: Drinking Water Directive

EIP: European Innovation Partnership

EPA: Environmental Protection Agency

ES: Ecosystem services

GHG: Greenhouse gas

GIS: Geographic Information System

IPBES: Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services

IPCC: Inter-Governmental Panel on Climate Change

K: Potassium

MA: Millennium Ecosystem Assessment

MAES: Mapping and Assessment of Ecosystem Services

MENE: Monitoring of Engagement with the Natural Environment

N: Nitrogen

NCP: Nature's Contributions to People

NHA: Natural Heritage Area

NPWS: National Parks and Wildlife Service

P: Phosphorus

POC: Particulate organic carbon

SAC: Special Area of Conservation

TAG: Technical Advisory Group

TEEP: The Economics of Ecosystems and Biodiversity

TON: Total organic nitrogen

TRP: Total reactive phosphorus

TTHM: Total trihalomethanes

UKNEA: UK National Ecosystem Assessment

WFD: Water Framework Directive

Appendices

Appendix 1: Cultural Ecosystem Services table

Reference list of peatland cultural ecosystem services and benefits combining categories from the CICES and other typologies.

CICES group	CICES Class	Cultural services enable	Cultural benefits	Example indicator/data
Physical and experiential interactions with	Characteristics of living systems that enable activities promoting health or enjoyment through *active/immersive interactions*	Recreation and ecotourism	Importance for outdoor recreation and activities. Health and wellbeing (walking, running, hiking, dog walking, foraging, orienteering, picnicking); Ecotourism-related opportunities (guided walks; conservation volunteering).	Visitor numbers to peatlands; Tourism revenue
	Characteristics of living systems that enable activities promoting health or enjoyment through *passive/observational interactions*	Nature-based activities	Wildlife observation & encounters, bird-watching, photography; pond dipping; connecting to nature; relaxing in nature; fresh air; recording species; volunteering; community events. Angling, shooting, fishing.	Social media photographs; number of bird-watchers
Intellectual and representative interactions with natural environment	Characteristics of living systems that enable scientific investigation or the creation of traditional ecological knowledge	Scientific	Source of knowledge on habitats, species, ecosystem processes, genetic resources (scientific research, ecological surveys). Local knowledge relating to cultural and social history; impacts of recreational use of site; areas or activities of concern.	Number of research projects and scientific studies
	Characteristics of living systems that enable education and training	Educational	Opportunities for formal education, such as school trips and nature walks, outdoor classrooms. Informal learning from guided walks, workshops, information boards, websites, books or direct contact with nature. Skills and knowledge gained from voluntary conservation activities (habitat management, citizen science).	Number of visitor centres, school visits, educational events
	Characteristics of living systems that are resonant in terms of culture or heritage	Cultural heritage	Peatlands as archives: historic records, archaeological artefacts (chalices, manuscripts), climate and paleo-ecological record; crafts (bog oak, reeds); intangible cultural heritage such as oral histories,	Number of monuments, archaeology, and historical sites

			practices, traditions, values; industrial heritage such as turf cutting and associated skills and tools; folklore and mythology; identity.	
	Characteristics of living systems that enable aesthetic experiences	Aesthetic	Aesthetic qualities associated with remoteness, open space, scenic views, tranquility (e.g. blanket bogs in Connemara); beauty of bogs and their distinctive plant & animal communities.	Social media photos; protected areas
Spiritual, symbolic and other interactions with natural environment	Elements of living systems that have symbolic meaning	Symbolic	Symbolic significance of iconic plant and animal species such as Bog cotton, Curlew, Irish hare; reflective qualities associated with wilderness, remoteness, and isolation; inspiration for visual arts, sculpture, literature, poetry, music, performing arts.	Species data; creative outputs
	Elements of living systems that have sacred or religious meaning	Spiritual/religious	Spirituality associated with wilderness. Prehistoric significance for rituals; Pilgrimage sites, holy places (Brigid's Way, Pollardstown Fen). Animals and plants considered to have sacred qualities. Notions of ecological and evolutionary connectedness and temporal continuity.	Number of sacred sites; religious trails
	Elements of living systems used for entertainment or representation	Entertainment	Open-air activities at peatland sites (organized sports events e.g. Lough Boora runs; art exhibitions; tourism). Inspiration for representing nature in films or books; social media; design.	Number of events; outputs; exhibitions
Other non-use value	Characteristics of living systems that have an existence value	Existence	Enjoyment or satisfaction provided by knowledge of existence of wild species and peatland wilderness.	Protected areas
	Characteristics of living systems that have a bequest value	Bequest	Conserving plants, animals, and ecosystems for experience and use by future generations (moral/ethical imperative).	Legacy donations to charity
Other		Sense of place[14]	The aspects of a place that make it special and distinctive. Can be rooted in ways of life and livelihoods (Irish midlands); include locally characteristic species, habitats, landscapes or features (Connemara); related to historic and cultural events; or places important to people for spiritual or emotional reasons.	Locally distinct features of landscape; cultural representations

[14] 'Sense of place' is not included as a separate category in CICES. However, Ryfield et al (2019) highlight the importance of sense of place as a category which integrates multiple CES and allows for the development of new sources of evidence and indicators for CES

		Social relations[15]	Social benefits relating to volunteering, community cohesion, social networks, community-based conservation activities.	Number of volunteers

References: Haines-Young and Potschin (2018), Parker et al. (2016), Waylen et al. (2016).

[15] ESMERALDA Project suggested that 'creation and maintenance of social relations' is a potential gap in the structure of CICES in relation to cultural services. In V5.1, social relations has not been included as it relates to outcomes within the social system (Haines-Young & Potschin, 2018).

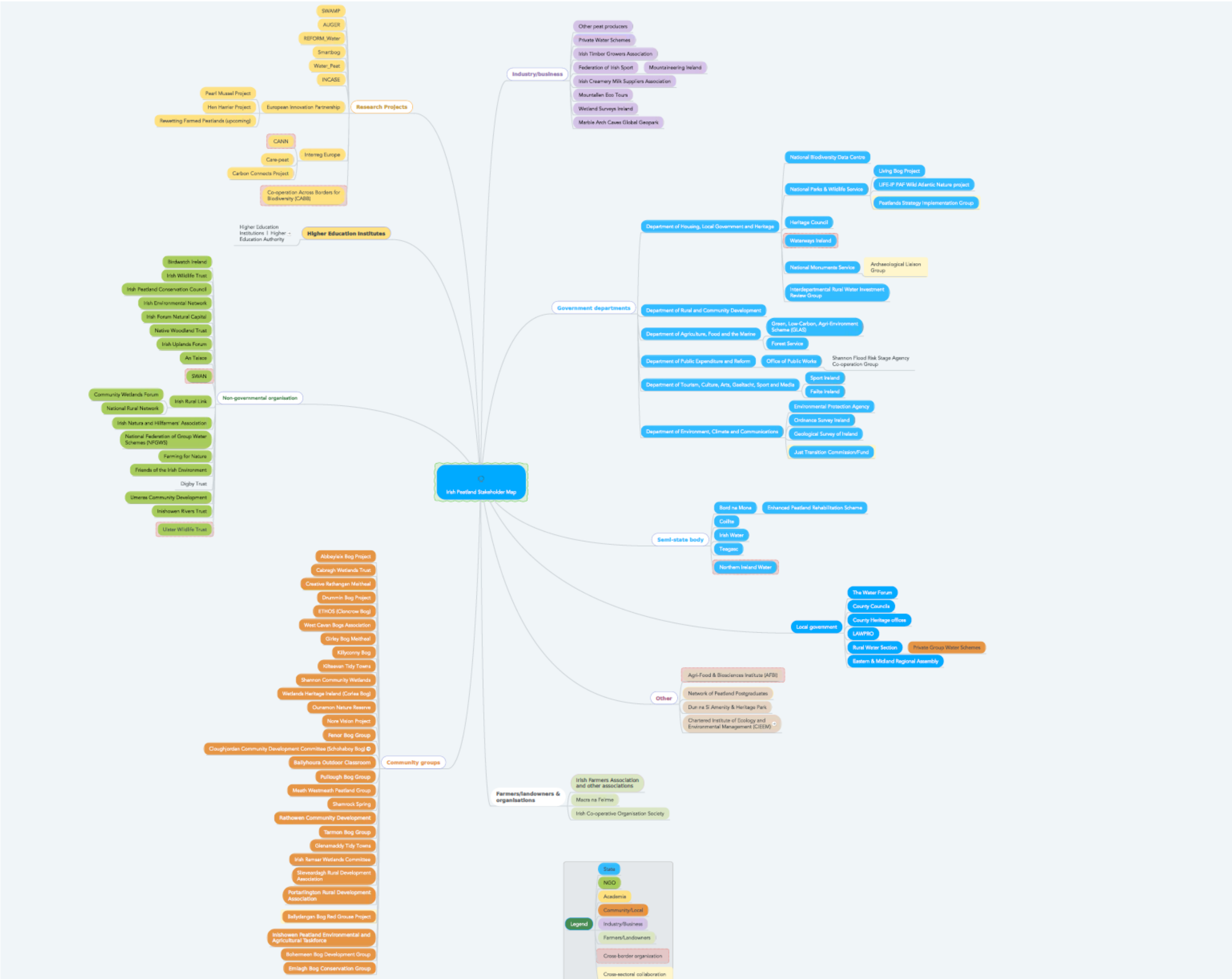
Appendix 2: Cultural Ecosystem Services classification

Classification system & associated CES definition	**Categorisation of CES**	**Uses/*Issues***
Millennium Ecosystem Assessment (MA) *"Cultural services are the nonmaterial benefits people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experiences"* (Sarukhán et al, 2005)	• Cultural diversity • Spiritual and religious values • Knowledge systems • Educational values • Inspiration • Aesthetic values • Social relations • Sense of place • Cultural heritage • Recreation and ecotourism	• Basis for other classification systems • Easy to understand • Broad in its remit, including knowledge systems, sense of place, and social relations • *Issues with differentiation between CES benefits and services*
The Economics of Ecosystems and Biodiversity (TEEB) *"Cultural Services include the non-material benefits people obtain from contact with ecosystems. They include aesthetic, spiritual and psychological benefits"* (Kumar, 2010)	• Recreation, mental and physical health • Tourism • Aesthetic appreciation and inspiration for culture, art and design • Spiritual experience & sense of place	• Economic valuations & methodologies • Costs associated with biodiversity loss and ecosystem degradation • *Incorporation of market logics into environment and conservation policy*
Common International Classification Ecosystem Services (CICES 5.1) *"Cultural services are the environmental settings, locations or situations that give rise to changes in the physical or mental states of people, and whose character are dependent on living processes, which can involve individual species, habitats and whole ecosystems"* (Haines-Young & Potschin, 2018)	• Physical interactions • Intellectual interactions • Spiritual interactions • Existence and bequest values	• Standardised system of classification of ES used in Europe • Integrated valuations • Biotic and abiotic levels • *Does not include sense of place, social relations*
System of Environmental-Economic Accounting - Ecosystem Accounting (SEEA-EA) *"Cultural services are the experiential and non-material services related to the perceived or realized qualities of ecosystem assets*	• Recreation-related services • Aesthetic enjoyment services • Education, scientific and research services • Spiritual, symbolic and artistic services	• An integrated measurement framework for ecosystem stocks (assets) and flows (services) to measure the contributions of ecosystems to economic activity • *Does not account for intrinsic values*

whose existence and functioning contributes to a range of cultural benefits derived by individuals" (UNCEEA, 2020)	• Ecosystem and species appreciation	
Intergovernmental Platform on Biodiversity & Ecosystem Services (IPBES) - Concept of "*Nature's contributions to people (NCP) refers to all the contributions that humanity obtains from nature. Ecosystem goods and services are included in this category" (Díaz, 2020)*	• Learning and inspiration • Physical and psychological experiences • Supporting identities	• Global, Regional, & National assessments • Including broader range of stakeholders • Integrating different disciplines and knowledge systems (local & indigenous) • Aspects of nature that are negative for people • *NCP as a new term potentially adding confusing*
UK National Ecosystem Assessment framework (UKNEA) CES as the environmental settings and cultural practices that benefit human wellbeing in material and non-material ways or *"the interactions between environmental spaces (i.e. physical localities or landscapes) and the activities that occur there"* (Bryce et al, 2016).	Environmental settings and cultural practices that provide benefits such as: • Identities – belonging, sense of place, spirituality • Experiences - inspiration, escape, tranquillity • Capabilities – knowledge, health	• Place based approach • Importance of relational values • Indicator development • *Categories of practices, identities, experiences, & capabilities potentially difficult to operationalise*
Life Framework of Values CES as 'living in' the world - *"How we live from the world reflects how the environment matters as a resource. <u>How we live in points to the world as a place that is the source or main stage of our life events, from where social and cultural values are born.</u> How we live with the world points to nature/non-humans as important others, and living as the world points to the more-than-human … as expressed in indigenous notions of oneness & kinship"* (Kenter, 2019)	• Cultural services can map to more than one frame but particularly associated with 'living in' frame • The importance of nature as place. How cultures and communities relate to place, forming and supporting cultural and personal identities	• Compatible with concepts of ES and NCP • Inclusive of relational and (articulated) intrinsic values of nature as well as instrumental values • Move away from primarily anthropocentric environmental valuation & decision-making • *May risk adding further categories and confusion to the debate*

References: Bryce et al. (2016), Díaz et al. (2020), Haines-Young and Potschin (2018), Kenter (2019), Sarukhán et al. (2005), UNCEEA (2020), Kumar (2010).

Appendix 3: Stakeholder map



An electronic version of the pdf can be viewed online using this link:

https://adobe.ly/3uaAfQV

Appendix 4: Stakeholder Survey

Number of respondents: 16

The aim of this survey is to identify where there are gaps, and where improvements could be made, in relation to communication between stakeholders involved in peatland management.

Q.1 Stakeholders identified as missing in the map

- ICMSA
- Carbon Connects Project should be listed under Interreg projects
- Wetland Surveys Ireland are private organisation providing advisory services relating to peatland ecology and management. WSI have developed using their own resources the Map of Irish Wetlands, a national dataset on the distribution of peatlands and other wetlands throughout Ireland.
- Interreg Europe Carbon Connect
- Carbon Connects, an Interreg Project that has been collaborating with the Pearl Mussel Project
- Irish Water

  Inishowen Rivers Trust

  IPEAT (Inishowen Peatland Environmental and Agricultural Taskforce), C/O Inishowen Farm Innovations, Drumfries, Clonmany, Co. Donegal
- Meath Westmeath Peatland Heritage Group
- IRWC – Irish Peatland Society
- The NMS/NMI/BNM Archaeological Liaison Group as established by the Code of Practice between the National Monuments Service, The National Museum of Ireland and Bord Na Mona.
- Marble arch caves global Geopark, Ulster Wildlife Trust ,CANN project, butterfly conservation CABB, gun clubs. "Legal eagles" researching land issues, Social scientists, County development companies linking body of which I forget the name. Source to tap
- Additional community or conservation groups include Slieve Ardagh Rural Development Association - who manage Loch Doire Bhile developed on cutaway near Lanespark; Portarlington Rural Development Association - who manage Derryounce amenity north of Portarlington; Ballydangan Red Grouse Project - Roscommon

Q.2 Can you identify where key collaboration pathways should be strengthened or where new collaboration pathways are needed? Collaboration pathways might include vertical (from local to landscape scales) and horizontal (cross-sectoral) collaborations.

Across the board, more collaboration is needed, horizontally, vertically, between disciplines, between sectors and at every scale.

Summary of themes:

1. Collaboration between r**esearch projects, applied projects such as EIPs, and research institutes** *(also collaboration between researchers and community groups)*
2. Collaboration between **private sector and industry**
3. Collaboration with **landowners** to enhance knowledge, overcome peatland stereotypes, show benefits and potential incomes
4. Horizontal collaboration between local groups, **communities and landowners**
5. Links between **local authorities** and those with **peatland management / ecology skills** (practitioners) - either through community liaison (LAWPRO, NPWS) or a **local network of ecologists.**
6. More links with **citizen science** (eyes on the bogs) initiatives
7. Blanket bogs – engage with farmers with agricultural activity
8. **Semi-state bodies and community groups**
9. **Researchers and community groups**
10. Strengthen collaboration between peatland managers (Bord na Mona) and other stakeholders
11. Collaboration with **NPWS and Rangers**
12. Organisations like **IFA and Farming for nature**

Full answers:

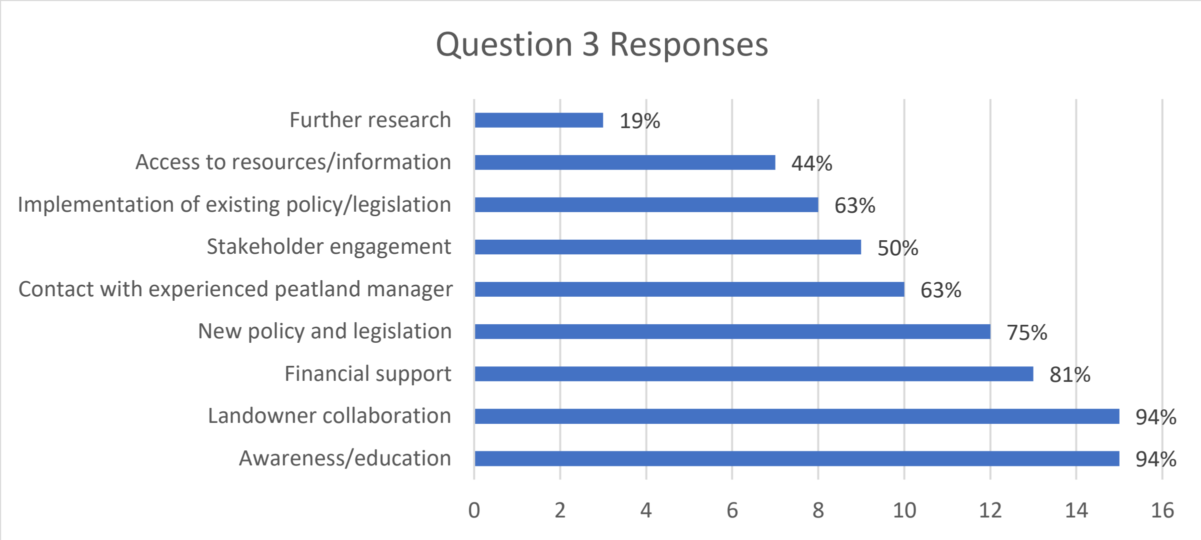
- **Strong links** and engagement between people who really know what they're talking about and local landowners. The **policy has to reflect this** also.
- **Increased collaboration** between research projects is needed. In particular between EIPs and projects run by research institutes.
- **Collaboration with private sector and industry** should be strengthened.
- I feel like **collaboration with landowners** should be strengthened, in order to enhance their knowledge about peatlands, change their perspective and stereotype that peatlands is a wasteland and show that alternative, more sustainable way for peatlands management can be beneficial to their land and profitable for them. Maybe horizontal collaboration between

local groups/communities/landowners should be targeted as well to give the feeling of the unity and common effort

- Need for greater collaboration between applied research projects such as EIPs and other research projects.
- Links between Local authorities and those peatland management / ecology skills - either through community liaison (LAWPRO, NPWS) or a local network of ecologists. More links with citizen science (eyes on the bogs) initiatives.
- In General, especially on Blanket bogs farmers with agricultural activity on the land must be engaged with
- 1. Semi-state bodies and community groups 2. Research and community groups
- Yes from the EPA to the NMS in terms of the licensing of peat extraction.
- Collaboration can always be strengthened between peatland managers (Bord na Mona) and other stakeholders!
- Network building is a complicated and slow moving process. In our area more communication with NPWS and our Ranger would be great. Also working with organisations like IFA and Farming for nature would be important

Q.3 What do you think is needed to enable management of peatlands for water quality, climate mitigation and biodiversity benefits?

Financial support and stakeholder engagement considered by respondents as the most important to enable peatland management, followed by landowner collaboration and increased awareness / education.



Key themes identified under 'Other':

- Incentivise delivery through results-based payments.
- Give back to local communities/society.
- Tap into resources from private industry.
- A proven delivery method.
- Changes to existing agricultural policy to ensure payments relate to positive environmental outcomes.
- Agricultural policy acknowledging public goods and ecosystem services provided by agricultural activity on peatlands.
- Management with consideration for archaeological structures in bogs.

Full answers under 'Other':

Agricultural policy needs to acknowledge the public goods and ecosystem services provided by agricultural activity on peatlands

A proven delivery method, changes to existing agri policy to ensure payments relate to positive environmental outcomes.

I believe resources from private industry have not been tapped into. Aware that industry / private sector would welcome opportunity to contribute towards peatland restoration. Motivation may be to off-set climate impact of operations or to give back to / support the local community / wider society.

I think you should also consider the benefits of managing peatlands for water quality in terms of the archaeological structures in bogs. To date 1000's of such structures, toghers, platforms, habitation *sites etc have been identified in industrial midland bogs, while boglands represent one of the most fruitful landscape types for artefact recovery and survival. Most of the important finds in the National Museum of Ireland came from bogs. The importance of regenerating boglands for the secure preservation of archaeological deposits should not be underestimated.*

Q 4 Please identify the two most important options from above which would help with peatland management in the short term?

Summary of themes:

1. **Meaningful engagement with landowners early in process, collaboration**
2. **Changing policy, new agri-policy – results based payments, discourage drainage**
3. **Implementing existing policy and legislation**
4. **Financial support for landowners (care, stewardship)**
5. **Recognising services from peatlands**
6. **High archaeological potential of all bogs**
7. **Support in local authorities - Biodiversity Officers are in place in each LA to support volunteers.**

Full answers:

- Experienced peatland managers **engaging with local landowners** along with **strong policy** in this area. The policy must be encouraging landowners to **engage and reward** them for this.
- Financial Support/Contact with experienced peatland managers
- 1. Change **agricultural policy** to focus more on **payments for results**, 2. landowner **collaboration**
- 1. Investment from private sector. 2. Change in agriculture policy towards outcome (results) based payments.
- In my opinion, the landowners can't change much in their the practice while the current legislation is in a favor of traditional agricultural practice of peatlands drainage. First, we need to provide them an **opportunity to benefit from wet peatlands**, not losing their subsidies for not drain their land. But more important is **implementation of these legislation**. So, implementation of existing policy and its further development towards more sustainable management of peatlands.
- New policy around **CAP - agri-environmental measures** more focused on **payment for results. Meaningful engagement** with landowners from earliest stage.

- New policy and legislation around recognizing the **services from peatlands** (as well as a baseline map to highlight areas that need care) and **financial support for landowners to administer that care.**
- Awareness/education, landowner collaboration
- Landowner collaboration. New **agricultural policy** to support farmers farming these areas
- Stakeholder engagement and Financial support
- **Implementation of existing policy and legislation** - ie Section 12 NMS 1994 Amendment Act in relation to the **extraction of peat on privately owned peatlands** and in relation to any proposed activities, drain blocking, etc on bogs.
  In addition we consider all bogs - whether archaeological features or artefacts have been identified within them as areas of **high archaeological potential** and the Department should be advised of any activity relating to them.
- Landholder collaboration, Financial support
- Stakeholder engagement, Landowner collaboration
- The two I would pick would be, Contact with experienced peatland managers and Landowner collaboration. I think the toughest thing is trying to pull together the people and time need to undertake projects on our peatlands. I think having the necessary **support in the local authorities** is essential and we need to make sure that **Biodiversity Officers** are in place in each LA to support our volunteers. Our HO has been great but it would be great to see his role more focused.

References

AALDERS, I. & STANIK, N. 2016. Data Gap Analysis for Cultural Ecosystem Services. Report for.

ALLOTT, N., BRENNAN, M., COOKE, D., REYNOLDS, J. & SIMON, N. 1997. A study of the effects of stream hydrology and water chemistry in forested catchments on fish and macroinvertebrates. AQUAFOR Report 4. Stream chemistry, hydrology and biota, Galway-Mayo region. . Dublin, Ireland.

ALM, J., SCHULMAN, L., WALDEN, J., NYKÄNEN, H., MARTIKAINEN, P. J. & SILVOLA, J. 1999. Carbon balance of a boreal bog during a year with an exceptionally dry summer. Ecology, 80, 161 - 174.

ALM, J., TALANOV, A., SAARNIO, S., SILVOLA, J., IKKONEN, E., AALTONEN, H., NYKÄNEN, H. & MARTIKAINEN, P. J. 1997. Reconstruction of the carbon balance for microsites in a boreal oligotrophic pine fen, Finland. Oecologia, 110, 423-431.

AN FÓRAM UISCE 2020. Framework for Integrated Land and Landscape Management.

ANDERSEN, R., ROCHEFORT, L. & LANDRY, J. 2011. La chimie des tourbières du Québec: une synthèse de 30 années de données. Le naturaliste canadien, 135, 5-14.

ARMSTRONG, A., HOLDEN, J., KAY, P., FRANCIS, B., FOULGER, M., GLEDHILL, S., MCDONALD, A. T. & WALKER, A. 2010. The impact of peatland drain-blocking on dissolved organic carbon loss and discolouration of water; results from a national survey. Journal of Hydrology, 381, 112-120.

ASAM, Z.-U.-Z., KAILA, A., NIEMINEN, M., SARKKOLA, S., O'DRISCOLL, C., O'CONNOR, M., SANA, A., RODGERS, M. & XIAO, L. 2012. Assessment of phosphorus retention efficiency of blanket peat buffer areas using a laboratory flume approach. Ecological Engineering, 49, 160-169.

ASAM, Z.-U.-Z., NIEMINEN, M., KAILA, A., LAIHO, R., SARKKOLA, S., O'CONNOR, M., O'DRISCOLL, C., SANA, A., RODGERS, M., ZHAN, X. & XIAO, L. 2014. Nutrient and heavy metals in decaying harvest residue needles on drained blanket peat forests. European Journal of Forest Research, 133, 969-982.

ASAM, Z.-U.-Z., O'DRISCOLL, C., ABBAS, M., O'CONNOR, M., WAQAS, M., REHAN, M., NIZAMI, A.-S. & XIAO, L. 2020. Mechanism and role of seeded native grasses to immobilize nitrogen on harvested blanket peat forests for protection of water courses. Environmental Science and Pollution Research.

BARRY, C., RENOU-WILSON, F., WILSON, D., MÜLLER, C. & FOY, R. 2016. Magnitude, form and bioavailability of fluvial carbon exports from Irish organic soils under pasture. Aquatic Sciences, 78, 541-560.

BEADLE, J. M., BROWN, L. E. & HOLDEN, J. 2015. Biodiversity and ecosystem functioning in natural bog pools and those created by rewetting schemes. WIREs Water, 2, 65-84.

BELL, M. C., RITSON, J. P., VERHOEF, A., BRAZIER, R. E., TEMPLETON, M. R., GRAHAM, N. J. D., FREEMAN, C. & CLARK, J. M. 2018. Sensitivity of peatland litter decomposition to changes in temperature and rainfall. Geoderma, 331, 29-37.

BELLISARI, L., DEODATI, T., OLMEDA, C. & GUIMARAES, A. 2017. Linking Natura 2000 and cultural heritage. EU document.

BELTMAN, B., KOOIJMAN, A. M., ROUWENHORST, G. & VAN KERKHOVEN, M. 1996. Nutrient Availability and Plant Growth Limitation in Blanket Mires in Ireland. Biology and Environment: Proceedings of the Royal Irish Academy, 96B, 77-87.

BENNETT, N. J., ROTH, R., KLAIN, S. C., CHAN, K., CHRISTIE, P., CLARK, D. A., CULLMAN, G., CURRAN, D., DURBIN, T. J. & EPSTEIN, G. 2017. Conservation social science: Understanding and integrating human dimensions to improve conservation. biological conservation, 205, 93-108.

BIDOGLIO, G. & STUMM, W. 2013. Chemistry of aquatic systems: local and global perspectives, Springer Science & Business Media.

BILLETT, M. F., CHARMAN, D. J., CLARK, J. M., EVANS, C. D., EVANS, M. G., OSTLE, N. J., WORRALL, F., BURDEN, A., DINSMORE, K. J., JONES, T., MCNAMARA, N. P., PARRY, L., ROWSON, J. G. & ROSE, R. 2010. Carbon balance of UK peatlands: current state of knowledge and future research challenges. Climate Research, 45, 13-29.

BLAIN, D., MURDIYARSO, D., COUWENBERG, J., NAGATA, O., RENOU-WILSON, F., SIRIN, A., STRACK, M., TUITTILA, E. S. & WILSON, D. 2014. Chapter 3. Rewetted organic soils. In: HIRAISHI, T., KRUG, T., TANABE, K., SRIVASTAVA, N., BAASANSUREN, J., FUKUDA, M. & TROXLER, T. G. (eds.) 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands. Switzerland: Intergovernmental Panel on Climate Change.

BONN, A., ALLOTT, T., EVANS, M., JOOSTEN, J. & STONEMAN, R. (eds.) 2016. Peatland restoration and ecosystem services, Cambridge: CUP.

BONN, A., REED, M. S., EVANS, C. D., JOOSTEN, H., BAIN, C., FARMER, J., EMMER, I., COUWENBERG, J., MOXEY, A. & ARTZ, R. 2014. Investing in nature: Developing ecosystem service markets for peatland restoration. Ecosystem Services, 9, 54-65.

BORD NA MÓNA. 2020a. Bord na Móna to commence Enhanced Peatland Rehabilitation Scheme [Online]. Available: https://www.bordnamona.ie/company/news/articles/bord-na-mona-to-commence-enhanced-peatland-rehabilitation-scheme/#:~:text=Enhanced%20rehabilitation%20involves%20a%20wide,wetlands%2C%20grasslands%20and%20native%20woodlands. [Accessed 30/11/2020].

BORD NA MÓNA 2020b. Planning Application: Appendix 4. Drainage – Design Principles and Standards.

BORD NA MÓNA. 2020c. Story of Original Maps [Online]. Available: https://www.bordnamonalivinghistory.ie/maps/history-of-maps/ [Accessed 12/06/2020].

BRESNIHAN, P. & HESSE, A. 2019. Desk Study on Public Engagement in Water Governance. An Fóram Uisce.

BROEKHUIZEN, N., PARKYN, S. & MILLER, D. 2001. Fine sediment effects on feeding and growth in the invertebrate grazers Potamopyrgus antipodarum (Gastropoda, Hydrobiidae) and Deleatidium sp.(Ephemeroptera, Leptophlebiidae). Hydrobiologia, 457, 125-132.

BRUMMELL, M. E., LAZCANO, C. & STRACK, M. 2017. The effects of Eriophorum vaginatum on N2O fluxes at a restored, extracted peatland. Ecological Engineering, 106, 287-295.

BRYCE, R., IRVINE, K. N., CHURCH, A., FISH, R., RANGER, S. & KENTER, J. O. 2016. Subjective well-being indicators for large-scale assessment of cultural ecosystem services. Ecosystem Services, 21, 258-269.

BUBIER, J. L., COSTELLO, A., MOORE, T. R., ROULET, N. T. & SAVAGE, K. 1993. Microtopography and methane flux in boreal peatlands, northern Ontario, Canada. Canadian Journal of Botany, 71, 1056-1063.

BUBIER, J. L., MOORE, T., SAVAGE, K. & CRILL, P. 2005. A comparison of methane flux in a boreal landscape between a dry and a wet year. Global Biogeochemical Cycles, 19, doi:10.1029/2004GB002351.

BULLOCK, C. 2017. Nature's values: From intrinsic to instrumental. A review of values and valuation methodologies in the context of ecosystem services and natural capital. National Economic and Social Council, 10.

BULLOCK, C. A role for diverse environmental values in bringing about policy change: an example from Ireland. Biology and Environment: Proceedings of the Royal Irish Academy, 2020. JSTOR, 115-122.

BULLOCK, C. & FLOOD, K. 2020. Guidelines for Communities Managing Local Wetlands and Peatlands.: Community Wetlands Forum.

BYG, A., MARTIN-ORTEGA, J., GLENK, K. & NOVO, P. 2017. Conservation in the face of ambivalent public perceptions–The case of peatlands as 'the good, the bad and the ugly'. Biological conservation, 206, 181-189.

CALLERY, O., BRENNAN, R. B. & HEALY, M. G. 2015. Use of amendments in a peat soil to reduce phosphorus losses from forestry operations. Ecological Engineering, 85, 193-200.

CAMARGO, J. A. & ALONSO, Á. 2006. Ecological and toxicological effects of inorganic nitrogen pollution in aquatic ecosystems: A global assessment. Environment International, 32, 831-849.

CARLIN, C., KINDERMANN, G., BRITTON, E., CORMICAN, M., DOMEGAN, C., GORMALLY, M. & O'DONOVAN, D. 2020. Nature and Environment to Attain and Restore Health (NEAR Health).

CARLING, P., IRVINE, B., HILL, A. & WOOD, M. 2001. Reducing sediment inputs to Scottish streams: a review of the efficacy of soil conservation practices in upland forestry. Science of the total environment, 265, 209-227.

CARROLL, P. & CRILL, P. 1997. Carbon balance of a temperate poor fen. Global Biogeochemical Cycles, 11, 349 - 356.

CHAN, K. M., GOULD, R. K. & PASCUAL, U. 2018. Editorial overview: Relational values: what are they, and what's the fuss about? : Elsevier.

CHAN, K. M., GUERRY, A. D., BALVANERA, P., KLAIN, S., SATTERFIELD, T., BASURTO, X., BOSTROM, A., CHUENPAGDEE, R., GOULD, R. & HALPERN, B. S. 2012. Where are cultural and social in ecosystem services? A framework for constructive engagement. BioScience, 62, 744-756.

CHAPMAN, S., BUTTLER, A., FRANCEZ, A.-J., LAGGOUN-DÉFARGE, F., VASANDER, H., SCHLOTER, M., COMBE, J., GROSVERNIER, P., HARMS, H. & EPRON, D. 2003. Exploitation of northern peatlands and biodiversity maintenance: a conflict between economy and ecology. Frontiers in Ecology and the Environment, 1, 525-532.

CHARMAN, D. 2002. Peatlands and Environmental Change, Chichester, John Wiley & Sons.

CHIMNER, R. A. & COOPER, D. J. 2003. Influence of water table levels on CO2 emissions in a Colorado subalpine fen: an in situ microcosm study. Soil Biology and Biochemistry, 35, 345-351.

CLARK, J. M., GALLEGO-SALA, A. V., ALLOTT, T. E. H., CHAPMAN, S. J., FAREWELL, T., FREEMAN, C., HOUSE, J. I., ORR, H. G., PRENTICE, I. C. & SMITH, P. 2010. Assessing the vulnerability of blanket peat to climate change using an ensemble of statistical bioclimatic envelope models. Climate Research, 45, 131-150.

CLIMATE CHANGE ADVISORY COUNCIL 2020. Annual Review 2020. In: COUNCIL, C. C. A. (ed.). Dublin: Climate Change Advisory Council.

CLYMO, R. S. 1984. The limits to peat bog growth. Philos. Trans. R. Soc. London B Biol. Sci, 303, 605-654.

CLYMO, R. S., TURUNEN, J. & TOLONEN, K. 1998. Carbon accumulation in peatland. Oikos, 81, 368-388.

COGGINS, A. M., JENNINGS, S. G. & EBINGHAUS, R. 2006. Accumulation rates of the heavy metals lead, mercury and cadmium in ombrotrophic peatlands in the west of Ireland. Atmospheric Environment, 40, 260-278.

COILLTE 2017. Outdoor recreation plan for public lands and waters in Ireland 2017-2021. .

COLL, J., BOURKE, D., HODD, R. L., SHEEHY SKEFFINGTON, M., GORMALLY, M. & SWEENEY, J. 2016. Projected climate change impacts on upland heaths in Ireland. Climate Research, 69, 177-191.

COLL, J., BOURKE, D., SKEFFINGTON, M. S., GORMALLY, M. & SWEENEY, J. 2014. Projected loss of active blanket bogs in Ireland. Climate Research, 59, 103-115.

COLLIER, M. J. & SCOTT, M. J. 2008. Industrially harvested peatlands and after-use potential: understanding local stakeholder narratives and landscape preferences. Landscape Research, 33, 439 - 460.

CONNOLLY, J. & HOLDEN, N. M. 2009. Mapping peat soils in Ireland: updating the derived Irish peat map. Irish Geography, 42, 343-352.

CONNOLLY, J. & HOLDEN, N. M. 2017. Detecting peatland drains with Object Based Image Analysis and Geoeye-1 imagery. Carbon Balance and Management, 12, 7.

CREEVY, A. L., PAYNE, R. J., ANDERSEN, R. & ROWSON, J. G. 2019. Annual gaseous carbon budgets of forest-to-bog restoration sites are strongly determined by vegetation composition. Science of The Total Environment, 135863.

CROWLEY, C., FLOOD, K., CAFFREY, B., DUNFORD, B., FITZPATRICK, Ú., HAMILTON, J. & O'GORMAN, M. Engaging and empowering people in biodiversity conservation: lessons from practice. Biology and Environment: Proceedings of the Royal Irish Academy, 2020. JSTOR, 175-185.

CRUICKSHANK, M. M., TOMLINSON, R. W., DEVINE, P. M. & MILNE, R. 1998. Carbon in the vegetation and soils of Northern Ireland. Biology and Environment-Proceedings of the Royal Irish Academy, 98B, 9-21.

CUMMINS, T. & FARRELL, E. P. 2003a. Biogeochemical impacts of clearfelling and reforestation on blanket-peatland streams: II. major ions and dissolved organic carbon. Forest Ecology and Management, 180, 557-570.

CUMMINS, T. & FARRELL, E. P. 2003b. Biogeochemical impacts of clearfelling and reforestation on blanket peatland streams I. phosphorus. Forest Ecology and Management, 180, 545-555.

CURREY, P. M., JOHNSON, D., SHEPPARD, L. J., LEITH, I. D., TOBERMAN, H., VAN DER WAL, R., DAWSON, L. A. & ARTZ, R. R. E. 2010. Turnover of labile and recalcitrant soil carbon differ in response to nitrate and ammonium deposition in an ombrotrophic peatland. Global Change Biology, 16, 2307-2321.

DAFM 2018. Forests & Water Achieving Objectives under Ireland's River Basin Management Plan 2018-2021.

DAFM 2020. Ag Climatise A roadmap towards climate neutrality. Dublin: Department of Agriculture, Food and the Marine.

DAHG 2015. National Landscape Strategy 2015-2025. . Dublin: Government of Ireland.

DALY, K., JEFFREY, D. & TUNNEY, H. 2001. The effect of soil type on phosphorus sorption capacity and desorption dynamics in Irish grassland soils. Soil Use and Management, 17, 12-20.

DANIELS, S. M., EVANS, M. G., AGNEW, C. T. & ALLOTT, T. E. H. 2012. Ammonium release from a blanket peatland into headwater stream systems. Environmental Pollution, 163, 261-272.

DAWSON, J. J., BILLETT, M. F., HOPE, D., PALMER, S. M. & DEACON, C. M. 2004. Sources and sinks of aquatic carbon in a peatland stream continuum. Biogeochemistry, 70, 71-92.

DCCAE 2019. Climatev action plan 2019.

DECC. 2020a. Bord Na Móna Bog Rehabilitation Scheme [Online]. Available: https://www.gov.ie/en/publication/136a7-bord-na-mona-bog-rehabilitation-scheme/ [Accessed].

DECC. 2020b. Cabinet approves €108m funding for groundbreaking Bord na Móna bog rehabilitation plan. [Online]. Available: https://www.gov.ie/en/press-release/2aae1-cabinet-approves-108m-funding-for-groundbreaking-bord-na-mona-bog-rehabilitation-plan-minister-ryan-also-announces-that-47-more-projects-in-the-midlands-totalling-278m-are-approved-under-the-just-transition-fund/ [Accessed November 2020].

DEPARTMENT OF HEALTH 2013. Healthy Ireland–A Framework for Improved Health and Wellbeing 2013–2025. Department of Health Dublin.

DEPARTMENT OF HOUSING, P. A. L. G. 2018. River Basin Management Plan 2018-2021. Dublin: Government of Ireland

DÍAZ, S., SETTELE, J., BRONDÍZIO, E., NGO, H., GUÈZE, M., AGARD, J., ARNETH, A., BALVANERA, P., BRAUMAN, K. & BUTCHART, S. 2020. Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services.

DICKINSON, D. C. & HOBBS, R. J. 2017. Cultural ecosystem services: Characteristics, challenges and lessons for urban green space research. Ecosystem Services, 25, 179-194.

DIELEMAN, C. M., LINDO, Z., MCLAUGHLIN, J. W., CRAIG, A. E. & BRANFIREUN, B. A. 2016. Climate change effects on peatland decomposition and porewater dissolved organic carbon biogeochemistry. Biogeochemistry, 128, 385-396.

DINSMORE, K., BILLETT, M. & DYSON, K. 2013. Temperature and precipitation drive temporal variability in aquatic carbon and GHG concentrations and fluxes in a peatland catchment. Global change biology, 19, 2133-2148.

DINSMORE, K. J., BILLETT, M. F., SKIBA, U. M., REES, R. M., DREWER, J. & HELFTER, C. 2010. Role of the aquatic pathway in the carbon and greenhouse gas budgets of a peatland catchment. Global Change Biology, 16, 2750-2762.

DOUGLAS, C., VALVERDE, F. F. & RYAN, J. Peatland habitat conservation in Ireland. In: FARRELL, C. A. & FEEHAN, J., eds. 13th International Peat Congress: After Wise-Use: The Future of Peatlands, 2008 Tullamore, Ireland. International Peat Society, 681-685.

DRINAN, T. J., GRAHAM, C. T., O'HALLORAN, J. & HARRISON, S. S. C. 2013. The impact of catchment conifer plantation forestry on the hydrochemistry of peatland lakes. Science of The Total Environment, 443, 608-620.

DRISCOLL, C. T., BAKER, J. P., BISOGNI, J. J. & SCHOFIELD, C. L. 1980. Effect of aluminium speciation on fish in dilute acidified waters. Nature, 284, 161-164.

DRÖSLER, M., VERCHOT, L., FREIBAUER, A., PAN, G., EVANS, C. D., BOURBONNIERE, R. A., ALM, J. P., PAGE, S., AGUS, F., HERGOUALC'H, K., COUWENBERG, J., JAUHIAINEN, J., SABIHAM, S., WANG, C., SRIVASTAVA, N., BOURGEAU-CHAVEZ, L. L., HOOIJER, A., MINKKINEN, K., FRENCH, N., STRAND, T., SIRIN, A., MICKLER, R., TANSEY, K. & LARKIN, N. 2014. Chapter 2: Drained Inland Organic Soils. In: HIRAISHI, T., KRUG, T., TANABE, K., SRIVASTAVA, N., BAASANSUREN, J., FUKUDA, M. & TROXLER, T. G. (eds.) 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands. Switzerland: Intergovernmental Panel on Climate Change.

DUFFY, P., BLACK, K., FAHEY, D., HYDE, B., KEHOE, A., MURPHY, J., QUIRKE, B., RYAN, A. M. & PONZI, J. 2020. Ireland National Inventory Report 2020—Greenhouse Gas Emissions 1990 - 2018 Reported to the United Nations Framework Convention on Climate Change. Johnstown Castle Estate, Co. Wexford, Ireland.: Environmental Protection Agency.

EARTH COUNCIL 2000. The earth charter. Costa Rica.

EATON, J. M., MCGOFF, N. M., BYRNE, K. A., LEAHY, P. & KIELY, G. 2008. Land cover change and soil organic carbon stocks in the Republic of Ireland 1851-2000. Climatic Change, 91, 317-334.

EPA. 2017. The Bord na Mona Raised Bog Restoration Project [Online]. Available: https://www.catchments.ie/bord-na-mona-raised-bog-restoration-project/#:~:text=The%20main%20objective%20of%20the,and%20restore%20peatland%20habitat%20function. [Accessed 14/08/2020].

EPA 2020a. Guidance on the process of preparing and implementing a bog rehabilitation plan. Web only: Environmental Protection Agency.

EPA 2020b. Ireland's Air Pollutant Emissions 1990-2030. EPA.

ES-SALHI, M. A., CLÉMENT, M., ST-HILAIRE, A., CAISSIE, D. & COURTENAY, S. C. 2013. Influence of hydrological conditions and peat extraction operations on suspended sediment concentration and deposition in the East Branch Portage River, New Brunswick (Canada). Water Quality Research Journal, 48, 305-320.

EUROPEAN COMMISSION 2011. Our life insurance, our natural capital: an EU biodiversity strategy to 2020. Communication from the Commission to the European Parliament, the Council, the Economic and Social Committee and the Committee of the Regions. Official Journal of the European Union.

EUROPEAN PARLIAMENT 2018. Regulation (EU) 2018/841 of the European Parliament and of the Council of 30 May 2018 on the inclusion of greenhouse gas emissions and removals from land use, land use change and forestry in the 2030 climate and energy framework, and amending Regulation (EU) No 525/2013 and Decision No 529/2013/EU.

EUROPEAN PARLIAMENT 2020. The European Green Deal. European Parliament resolution of 15 January 2020 on the European Green Deal (2019/2956(RSP).

EVANS, C., RENOU-WILSON, F. & STRACK, M. 2016a. The role of waterborne carbon in the greenhouse gas balance of drained and re-wetted peatlands. Aquatic Sciences, 78, 573-590.

EVANS, C., RITSON, J., MCADAM, J. H., CARTER, S., STANWORTH, A. & ROSS, K. 2020. A scoping study for potential community-based carbon offsetting schemes in the Falkland Islands. Report to Falklands Conservation, Stanley.

EVANS, C. D., BONN, A., HOLDEN, J., REED, M. S., EVANS, M. G., WORRALL, F., COUWENBERG, J. & PARNELL, M. 2014. Relationships between anthropogenic pressures and ecosystem functions in UK blanket bogs: Linking process understanding to ecosystem service valuation. Ecosystem Services, 9, 5-19.

EVANS, C. D., CHAPMAN, P. J., CLARK, J. M., MONTEITH, D. T. & CRESSER, M. S. 2006. Alternative explanations for rising dissolved organic carbon export from organic soils. Global Change Biology, 12, 2044-2053.

EVANS, M. & LINDSAY, J. 2010. Impact of gully erosion on carbon sequestration in blanket peatlands. Climate Research, 45, 31-41.

EVANS, M. & WARBURTON, J. 2001. Transport and dispersal of organic debris (peat blocks) in upland fluvial systems. Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group, 26, 1087-1102.

FARRELL, C. A. & DOYLE, G. J. 2003. Rehabilitation of industrial cutaway Atlantic blanket bog in County Mayo, North-West Ireland. Wetlands Ecology and Management, 11, 21-35.

FEALY, R., BRUYÉRE, C. & DUFFY, C. 2018. Regional Climate Model Simulations for Ireland for the 21st Century. EPA Research Report (2011-CCRP-MS-2.2). Johnstown Castle, Co. Wexford, Ireland.

FEEHAN, J., O'DONOVAN, G., RENOU-WILSON, F. & WILSON, D. 2008. The Bogs of Ireland: an Introduction to the Natural, Cultural and Industrial Heritage of Irish Peatlands–Revised Edition. UCD School of Biology and Environmental Science, Dublin.

FEELEY, H. B., BRUEN, M., BLACKLOCKE, S. & KELLY-QUINN, M. 2013. A regional examination of episodic acidification response to reduced acidic deposition and the influence of plantation forests in Irish headwater streams. Science of The Total Environment, 443, 173-183.

FENNER, N., FREEMAN, C., HUGHES, S. & REYNOLDS, B. 2001. Molecular weight spectra of dissolved organic carbon in a rewetted Welsh peatland and possible implications for water quality. Soil Use and Management, 17, 106-112.

FERNANDEZ-VALVERDE, F., MACGOWAN, F., FARRELL, M., CROWLEY, W., CROAL, Y., FANNING, M. & MCKEE, A. 2006. Assessment of the Impacts of Turf Cutting on Designated Raised Bogs. National Parks and Wildlife Service, Department of Environment, Heritage and Local Government, 85.

FERNANDEZ, F., CONNOLLY, K., CROWLEY, W., DENYER, J., DUFF, K. & SMITH, G. 2014. Raised bog monitoring and assessment survey 2013. Irish Wildlife Manuals, No. 81. National Parks and Wildlife Service, Department of Arts, Heritage and Gaeltacht, Dublin, Ireland.

FERNANDEZ, F. & CROWLEY, W. 2020. Abbeyleix Bog 2020 ecotope survey report. . Ireland: Ecology and Environmental Consultants Ireland Ltd.

FERRETTO, A., BROOKER, R., AITKENHEAD, M., MATTHEWS, R. & SMITH, P. 2019. Potential carbon loss from Scottish peatlands under climate change. Regional Environmental Change, 19, 2101-2111.

FINNEGAN, J., REGAN, J. T., DE EYTO, E., RYDER, E., TIERNAN, D. & HEALY, M. G. 2012. Nutrient dynamics in a peatland forest riparian buffer zone and implications for the establishment of planted saplings. Ecological Engineering, 47, 155-164.

FINNEGAN, J., REGAN, J. T., O’CONNOR, M., WILSON, P. & HEALY, M. G. 2014. Implications of applied best management practice for peatland forest harvesting. Ecological Engineering, 63, 12-26.

FIRESTONE, M. K. & DAVIDSON, E. A. 1989. Microbiological basis of NO and N2O production and consumption in soil. Exchange of trace gases between terrestrial ecosystems and the atmosphere, 47, 7-21.

FISH, R., CHURCH, A. & WINTER, M. 2016. Conceptualising cultural ecosystem services: A novel framework for research and critical engagement. Ecosystem Services, 21, 208-217.

FOREST SERVICE 2000. Forest Harvesting and Environment Guidelines. . Dublin, Ireland: Forest Service, Department of the Marine and Natural Resources.

FOSS, P. J., O'CONNELL, C. & CRUSHELL, P. H. 2001. Bogs & Fens of Ireland: Conservation Plan 2005, Irish Peatland Conservation Council.

FOSS, P. J. & O'CONNELL, C. A. 1998. The IPCC Peatland Conservation and Management Handbook, Irish Peatland Conservation Council.

FOSSITT, J. A. 2000. A guide to habitats in Ireland, Dublin, The Heritage Council.

FOULDS, S. A. & WARBURTON, J. 2007a. Significance of wind-driven rain (wind-splash) in the erosion of blanket peat. Geomorphology, 83, 183-192.

FOULDS, S. A. & WARBURTON, J. 2007b. Wind erosion of blanket peat during a short period of surface desiccation (North Pennines, Northern England). Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group, 32, 481-488.

FRANCEZ, A.-J., GOGO, S. & JOSSELIN, N. 2000. Distribution of potential CO2 and CH4 productions, denitrification and microbial biomass C and N in the profile of a restored peatland in Brittany (France). European Journal of Soil Biology, 36, 161-168.

FREEMAN, C., LOCK, M. A. & REYNOLDS, B. 1992. Fluxes of CO2, CH4 and N2O from a Welsh peatland following simulation of water table draw-down: Potential feedback to climatic change. Biogeochemistry, 19, 51-60.

FROLKING, S. & ROULET, N. T. 2007. Holocene radiative forcing impact of northern peatland carbon accummulation and methane emissions. Global Change Biology, 13, 1079-1088.

GAFFNEY, P. P. J., HANCOCK, M. H., TAGGART, M. A. & ANDERSEN, R. 2020. Restoration of afforested peatland: Immediate effects on aquatic carbon loss. Science of The Total Environment, 742, 140594.

GALAND, P. E., SAARNIO, S., FRITZE, H. & YRJÄLÄ, K. 2002. Depth related diversity of methanogen Archaea in Finnish oligotrophic fen. FEMS Microbiology Ecology, 42, 441-449.

GEURTS, J. J. M., OEHMKE, C., LAMBERTINI, C., ELLER, F., SORRELL, B. K., MANDIOLA, S. R., GROOTJANS, A. P., BRIX, H., WICHTMANN, W., LAMERS, L. P. M. & FRITZ, C. 2020. Nutrient removal potential and biomass production by Phragmites australis and Typha latifolia on European rewetted peat and mineral soils. Science of The Total Environment, 141102.

GIBSON, H. S., WORRALL, F., BURT, T. P. & ADAMSON, J. K. 2009. DOC budgets of drained peat catchments: implications for DOC production in peat soils. Hydrological Processes, 23, 1901-1911.

GLEBOV, F. Z., KARPENKO, L. V. & DASHKOVSKAYA, I. S. 2002. Climatic changes, succession of peatlands and zonal vegetation, and peat accumulation dynamics in the Holocene (the West - Siberia peat profile "Vodorasdel"). Climatic Change, 55, 175-181.

GOTTWALD, F. & SEUFFERT, A. 2005. Rewetting of the mesotrophic terrestrialization mire “Mellnsee” (Germany) - raising water level versus nutrient input. In: KOTOWSKI, W. (ed.) Anthropogenic Influence on Wetlans Biodiversity and Sustainable Management of Wetlands. Warsaw, Poland: Warsaw Agricultural University Press.

GOVERNMENT OF IRELAND 2018. River Basin Management Plan for Ireland 2018-2021. Dublin.

GRAU-ANDRÉS, R., DAVIES, G. M., GRAY, A., SCOTT, E. M. & WALDRON, S. 2018. Fire severity is more sensitive to low fuel moisture content on Calluna heathlands than on peat bogs. Science of The Total Environment, 616-617, 1261-1269.

GREEN, S. 2020. Distribution of cultivated peats. https://www.teagasc.ie/rural-economy/rural-economy/spatial-analysis/gis-monthly-maps/.

GRIFFIS, T. J. & ROUSE, W. R. 2001. Modelling the interannual variability of net ecosystem CO2 exchange at a subarctic sedge fen. Global Change Biology, 7, 511-530.

GÜNTHER, A., BARTHELMES, A., HUTH, V., JOOSTEN, H., JURASINSKI, G., KOEBSCH, F. & COUWENBERG, J. 2020. Prompt rewetting of drained peatlands reduces climate warming despite methane emissions. Nature Communications, 11, 1644.

HAFDHI, S., DUCHESNE, S. & ST-HILAIRE, A. 2020. Hydraulic modelling for assessment of the performance of sedimentation basins downstream from extracted peatlands. Mires and Peat, 26, 1-19.

HAINES-YOUNG, R. & POTSCHIN, M. B. 2018. Common international classification of ecosystem services (CICES) V5. 1 and guidance on the application of the revised structure. European Environment Agency, 53.

HAMMOND, R. F. 1981. The peatlands of Ireland. Soil Survey Bulletin No. 35, Dublin, Ireland, An Foras Taluntais.

HARPENSLAGER, S. F., VAN DEN ELZEN, E., KOX, M. A. R., SMOLDERS, A. J. P., ETTWIG, K. F. & LAMERS, L. P. M. 2015. Rewetting former agricultural peatlands: Topsoil removal as a prerequisite to avoid strong nutrient and greenhouse gas emissions. Ecological Engineering, 84, 159-168.

HARRIS, L. I., ROULET, N. T. & MOORE, T. R. 2020. Drainage reduces the resilience of a boreal peatland. Environmental Research Communications, 2, 065001.

HEIDERSCHEIDT, E., LEIVISKAE, T. & KLØVE, B. 2016. Coagulation of humic waters for diffused pollution control and the influence of coagulant type on DOC fractions removed. Journal of environmental management, 181, 883-893.

HEIDERSCHEIDT, E., RONKANEN, A.-K. & KLÖVE, B. 2013. Optimization of water treatment methods for the purification of peat extraction derived runoff: Evaluation of chemical treatment response to variations in incoming water quality using a 2k factorial test design.

HEIKKINEN, K., KARPPINEN, A., KARJALAINEN, S. M., POSTILA, H., HADZIC, M., TOLKKINEN, M., MARTTILA, H., IHME, R. & KLØVE, B. 2018. Long-term purification efficiency and factors affecting performance in peatland-based treatment wetlands: An analysis of 28 peat extraction sites in Finland. Ecological Engineering, 117, 153-164.

HELFTER, C., CAMPBELL, C., DINSMORE, K. J., DREWER, J., COYLE, M., ANDERSON, M., SKIBA, U., NEMITZ, E., BILLETT, M. F. & SUTTON, M. A. 2015. Drivers of long-term variability in CO₂ net ecosystem exchange in a temperate peatland. Biogeosciences, 12, 1799-1811.

HIGGINS, T. 2006. Returning to the Wild: Creating Lakes on Industrial Cutaway Peatlands in Ireland. Book Reviews, 6, 11.

HIRONS, M., COMBERTI, C. & DUNFORD, R. 2016. Valuing cultural ecosystem services. Annual Review of Environment and Resources, 41, 545-574.

HOLDEN, J., CHAPMAN, P. J. & LABADZ, J. C. 2004. Artificial drainage of peatlands: hydrological and hydrochemical process and wetland restoration. Progress in Physical Geography: Earth and Environment, 28, 95-123.

HOLDEN, J., EVANS, M. G., BURT, T. P. & HORTON, M. 2006. Impact of Land Drainage on Peatland Hydrology. Journal of Environmental Quality, 35, 1764-1778.

HOLDEN, J., WALLAGE, Z. E., LANE, S. N. & MCDONALD, A. T. 2011. Water table dynamics in undisturbed, drained and restored blanket peat. Journal of Hydrology, 402, 103-114.

HÖLL, B. S., FIEDLER, S., JUNGKUNST, H. F., KALBITZ, K., FREIBAUER, A., DRÖSLER, M. & STAHR, K. 2009. Characteristics of dissolved organic matter following 20years of peatland restoration. Science of The Total Environment, 408, 78-83.

HUGHES, S., REYNOLDS, B., BRITTAIN, S. A., HUDSON, J. A. & FREEMAN, C. 1998. Temporal trends in bromide release following rewetting of a naturally drained gully mire. Soil Use and Management, 14, 248-251.

HUTTUNEN, J. T., NYKANEN,H., TURUNEN,J., AND MARTIKAINEN,P.J. 2003. Methane emissions from natural peatlands in the northern boreal zone in Finland, Fennoscandia. Atmospheric Environment, 37: 147-151.

INTERNATIONAL CIVIL AVIATION ORGANISATION (ICAO) 2016. What would be the impact of a global MBM scheme for international aviation? .

IPCC 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. In: STOCKER, T. F., QIN, D., PLATTNER, G.-K., TIGNOR, M., ALLEN, S. K., BOSCHUNG, J., NAUELS, A., XIA, Y., BEX, V. & MIDGLEY, P. M. (eds.). Cambridge, United Kingdom and New York, NY, USA,.

IPCC 2014. 2013 Supplement to the 2006 Inter-Governmental Panel on Climate Change Guidelines for National Greenhouse Gas Inventories: Wetlands, IPCC, Switzerland.

IPCC 2018. Summary for Policymakers. In: MASSON-DELMOTTE, V., ZHAI, P., PÖRTNER, H.-O., ROBERTS, D., SKEA, J., SHUKLA, P. R., PIRANI, A., MOUFOUMA-OKIA, W., PÉAN, C., PIDCOCK, R.,

CONNORS, S., MATTHEWS, J. B. R., CHEN, Y., ZHOU, X., GOMIS, M. I., LONNOY, E., MAYCOCK, T., TIGNOR, M. & WATERFIELD, T. (eds.) An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development,and efforts to eradicate poverty.

IRISH WATER 2016. Water Supply project Eastern and Midlands Region. Preliminary options Appraisal Report. Volume 2. Appendices A, B, C & D. http://www.watersupplyproject.ie/wp-content/uploads/2015/11/Vol-2_Appendix-ABCD.pdf.

IUCN. 2020. Eyes on the Bog [Online]. Available: https://www.iucn-uk-peatlandprogramme.org/get-involved/eyes-bog [Accessed].

IVES, C. D. & KENDAL, D. 2014. The role of social values in the management of ecological systems. Journal of environmental management, 144, 67-72.

JACOBS, S., DENDONCKER, N., MARTÍN-LÓPEZ, B., BARTON, D. N., GOMEZ-BAGGETHUN, E., BOERAEVE, F., MCGRATH, F. L., VIERIKKO, K., GENELETTI, D. & SEVECKE, K. J. 2016. A new valuation school: integrating diverse values of nature in resource and land use decisions. Ecosystem Services, 22, 213-220.

JAHANGIR, M. M. R., FENTON, O., CAROLAN, R., HARRINGTON, R., JOHNSTON, P., ZAMAN, M., RICHARDS, K. G. & MÜLLER, C. 2020. Application of 15N tracing for estimating nitrogen cycle processes in soils of a constructed wetland. Water Research, 183, 116062.

JÄRVEOJA, J., PEICHL, M., MADDISON, M., SOOSAAR, K., VELLAK, K., KAROFELD, E., TEEMUSK, A. & MANDER, Ü. 2016. Impact of water table level on annual carbon and greenhouse gas balances of a restored peat extraction area. Biogeosciences, 13, 2637.

JAX, K., BARTON, D. N., CHAN, K. M., DE GROOT, R., DOYLE, U., ESER, U., GÖRG, C., GÓMEZ-BAGGETHUN, E., GRIEWALD, Y. & HABER, W. 2013. Ecosystem services and ethics. Ecological Economics, 93, 260-268.

JENNINGS, E., ALLOTT, N., PIERSON, D. C., SCHNEIDERMAN, E. M., LENIHAN, D., SAMUELSSON, P. & TAYLOR, D. 2009. Impacts of climate change on phosphorus loading from a grassland catchment: Implications for future management. Water Research, 43, 4316-4326.

JENNINGS, E., NICAONGHUSA, C., ALLOTT, N., NADEN, P., O'HEA, B., PIERSON, D. & SCHNEIDERMAN, E. 2006. Future climate change and water colour in Irish peatland catchments: results from the CLIME project. Environmental Pollution, 116, 143-14.

JOABSSON, A., RØJLE CHRISTENSEN, T. & WALLEN, B. 1999. Vascular plant controls on methane emisssions from northern peatforming wetlands. Trends in Ecology and Evolution, 14, 385-388.

JOENSUU, S., AHTI, E. & VUOLLEKOSKI, M. 2002. Effects of ditch network maintenance on the chemistry of run-off water from peatland forests. Scandinavian Journal of Forest Research, 17, 238-247.

JOHNSON, J. A., AHERNE, J. & CUMMINS, T. 2013. Contrasting responses of two Sitka spruce forest plots in Ireland to reductions in sulphur emissions: results of 20 years of monitoring. Biogeochemistry, 116, 15-37.

JONES, M. B., DONNELLY, A. & ALBANITO, F. 2006. Responses of Irish vegetation to future climate change. Biology and Environment: Proceedings of the Royal Irish Academy, 106B, 323-334.

JOOSTEN, H. & COUWENBERG, J. 2008. Peatlands and carbon. Assessment on Peatlands, Biodiversity and Climate Change.

JORDAN, S., STRÖMGREN, M., FIEDLER, J., LUNDIN, L., LODE, E. & NILSSON, T. 2016. Ecosystem respiration, methane and nitrous oxide fluxes from ecotopes in a rewetted extracted peatland in Sweden. Mires and Peat, 17, 1-23.

JUERGES, N. & KROTT, M. 2017. Deliverable 4.1 – Report on actors driving forest management in selected European countries. ALTERFOR deliverable report.

JUSZCZAK, R. & AUGUSTIN, J. 2013. Exchange of the greenhouse gases methane and nitrous oxide between the atmosphere and a temperate peatland in Central Europe. Wetlands, 33, 895-907.

KAILA, A., ASAM, Z., KOSKINEN, M., UUSITALO, R., SMOLANDER, A., KIIKKILÄ, O., SARKKOLA, S., O'DRISCOLL, C., KITUNEN, V. & FRITZE, H. 2016. Impact of re-wetting of forestry-drained peatlands on water quality—a laboratory approach assessing the release of P, N, Fe, and dissolved organic carbon. Water, Air, & Soil Pollution, 227, 292.

KAILA, A., SARKKOLA, S., LAURÉN, A., UKONMAANAHO, L., KOIVUSALO, H., XIAO, L., O'DRISCOLL, C., TERVAHAUTA, A. & NIEMINEN, M. 2014. Phosphorus export from drained Scots pine mires after clear-felling and bioenergy harvesting. Forest Ecology and Management, 325, 99-107.

KAKAEI LAFDANI, E., SAARELA, T., LAURÉN, A., PUMPANEN, J. & PALVIAINEN, M. 2020. Purification of Forest Clear-Cut Runoff Water Using Biochar: A Meso-Scale Laboratory Column Experiment. Water, 12, 478.

KÄKI, T., OJALA, A. & KANKAALA, P. 2001. Diel variation in methane emissions from stands of Phragmites australis (Cav.) Trin. ex Steud and Typha latifolia L. in a boreal lake. Aquatic Botany, 71, 259 - 271.

KANDEL, T. P., LÆRKE, P. E., HOFFMANN, C. C. & ELSGAARD, L. 2019. Complete annual CO2, CH4, and N2O balance of a temperate riparian wetland 12 years after rewetting. Ecological Engineering, 127, 527-535.

KELLY-QUINN, M., BRUEN, M., HARRISON, S., HEALY, M., CLARKE, J., DRINAN, T., FEELEY, H. B., FINNEGAN, J., GRAHAM, C. & REGAN, J. 2016. HYDROFOR: Assessment of the impacts of forest operations on the ecological quality of water. EPA Report.

KELLY-QUINN, M., TIERNEY, D., COYLE, S. & BRACKEN, J. 1997. A study of the effects of stream hydrology and water quality in forested catchments on fish and invertebrates. AQUAFOR Report 3. Stream Chemistry, Hydrology and Biota, Wicklow Region. . COFORD, Dublin, Ireland.

KELLY, F. 2000. Early Irish Farming. Dublin Institute for Advanced Studies. Reprinted by the School of Celtic Studies, Dublin Institute for Advanced Studies, Dublin.

KELLY, L. & SCHOUTEN, M. 2002. Vegetation. Conservation and Restoration of Raised Bogs: Geological, Hydrological and Ecological Studies. . Dublin, Ireland/ Staatabosbeheer, The Netherlands: Department of Environment and Local Government.

KENTER, J. O. 2019. Demystifying shared and social values- Valuing nature paper.

KENTTÄMIES, K. 1981. The effects on water quality of forest drainage and fertilization in peatlands.

KETTUNEN, A. 2003. Connecting methane fluxes to vegetation cover and water table fluctuations at microsite level: a modeling study. Global Biogeochemical Cycles, 17, 1051, doi: 10.1029/2002GB001958.

KLØVE, B. Leaching of nitrogen and phosphorus from a cutover peatland. Pages 879-886 in Proceedings of the 11th International Peat Congress. IPS. 11th International Peat Congress, IPS, 2000 Quebec. 879-886.

KLØVE, B. 2001. Characteristics of nitrogen and phosphorus loads in peat mining wastewater. Water Research, 35, 2353-2362.

KLØVE, B., SVEISTRUP, T. E. & HAUGE, A. 2010. Leaching of nutrients and emission of greenhouse gases from peatland cultivation at Bodin, Northern Norway. Geoderma, 154, 219-232.

KOEHLER, A.-K., MURPHY, K., KIELY, G. & SOTTOCORNOLA, M. 2009. Seasonal variation of DOC concentration and annual loss of DOC from an Atlantic blanket bog in South Western Ireland. Biogeochemistry, 95, 231-242.

KOEHLER, A.-K., SOTTOCORNOLA, M. & KIELY, G. 2011. How strong is the current carbon sequestration of an Atlantic blanket bog? Global Change Biology, 17, 309-319.

KOSKINEN, M., TAHVANAINEN, T., SARKKOLA, S., MENBERU, M. W., LAURÉN, A., SALLANTAUS, T., MARTTILA, H., RONKANEN, A.-K., PARVIAINEN, M., TOLVANEN, A., KOIVUSALO, H. & NIEMINEN, M. 2017. Restoration of nutrient-rich forestry-drained peatlands poses a risk for high exports of dissolved organic carbon, nitrogen, and phosphorus. Science of The Total Environment, 586, 858-869.

KÖSTER, E., PUMPANEN, J., PALVIAINEN, M., ZHOU, X. & KÖSTER, K. 2020. Effect of biochar amendment on the properties of growing media and growth of containerized Norway spruce, Scots pine, and silver birch seedlings. Canadian Journal of Forest Research.

KUMAR, P. 2010. The economics of ecosystems and biodiversity: ecological and economic foundations, UNEP/Earthprint.

LAINE, A., WILSON, D., KIELY, G. & BYRNE, K. A. 2007. Methane flux dynamics in an Irish lowland blanket bog. Plant and Soil, 299, 181-193.

LAROSE, S., PRICE, J. & ROCHEFORT, L. 1997. Rewetting of a cutover peatland: hydrologic assessment. Wetlands, 17, 416-423.

LAVOIE, C., GROSVERNIER, P., GIRARD, M. & MARCOUX, K. 2003. Spontaneous revegetation of mined peatlands: An useful restoration tool? Wetlands Ecology and Management, 11, 97-107.

LEDESMA, J. L., KÖHLER, S. J. & FUTTER, M. N. 2012. Long-term dynamics of dissolved organic carbon: implications for drinking water supply. Science of the total Environment, 432, 1-11.

LEPPELT, T., DECHOW, R., GEBBERT, S., FREIBAUER, A., LOHILA, A., AUGUSTIN, J., DRÖSLER, M., FIEDLER, S., GLATZEL, S. & HÖPER, H. 2014. Nitrous oxide emission budgets and land-use driven hotspots for organic soils in Europe.

LIGHT, A. 2002. Contemporary environmental ethics from metaethics to public philosophy. Metaphilosophy, 33, 426-449.

LUCEY, J., BOWMAN, J. J., CLABBY, K. J., CUNNINGHAM, P., LEHANE, M., MACCÁRTAIGH, M., MCGARRIGLE, M. & TONER, P. F. 1999. Water Quality in Ireland. Wexford: EPA.

LUNDHOLM, A., BLACK, K., CORRIGAN, E. & NIEUWENHUIS, M. 2020a. Evaluating the Impact of Future Global Climate Change and Bioeconomy Scenarios on Ecosystem Services Using a Strategic Forest Management Decision Support System. Frontiers in Ecology and Evolution, 8, 200.

LUNDHOLM, A., BLACK, K., CORRIGAN, E., NIEUWENHUIS, M. & HARPER, C. 2020b. Alternative forest management to address future challenges in Ireland's western peatland forests.

LUNDIN, L., NILSSON, T., JORDAN, S., LODE, E. & STRÖMGREN, M. 2017. Impacts of rewetting on peat, hydrology and water chemical composition over 15 years in two finished peat extraction areas in Sweden. Wetlands Ecology and Management, 25, 405-419.

LUYET, V., SCHLAEPFER, R., PARLANGE, M. B. & BUTTLER, A. 2012. A framework to implement stakeholder participation in environmental projects. Journal of Environmental Management, 111, 213-219.

MABERLY, S. C., KING, L., DENT, M. M., JONES, R. I. & GIBSON, C. E. 2002. Nutrient limitation of phytoplankton and periphyton growth in upland lakes. Freshwater Biology, 47, 2136-2152.

MACKIN, F., BARR, A., RATH, P., EAKIN, M., RYAN, J., JEFFREY, R. & FERNANDEZ VALVERDE, F. 2017. Best practice in raised bog restoration in Ireland. Irish Wildlife Manuals, No. 99. National Parks and Wildlife Service, Department of Culture, Heritage and the Gaeltacht, Ireland.

MÄKIRANTA, P., LAIHO, R., FRITZE, H., HYTÖNEN, J., LAINE, J. & MINKKINEN, K. 2009. Indirect regulation of heterotrophic peat soil respiration by water level via microbial community structure and temperature sensitivity. Soil Biology and Biochemistry, 41, 695-703.

MALONE, S. & O'CONNELL, C. 2009. Ireland's Peatland Conservation Action Plan 2020–halting the loss of peatland biodiversity. Irish Peatland Conservation Council, Kildare.

MARTIKAINEN, P. J., NYKÄNEN, H., CRILL, P. & SILVOLA, J. 1993. Effect of a lowered water table on nitrous oxide fluxes from northern peatlands. Nature, 366, 51-53.

MARTÍN-LÓPEZ, B., GÓMEZ-BAGGETHUN, E., GARCÍA-LLORENTE, M. & MONTES, C. 2014. Trade-offs across value-domains in ecosystem services assessment. Ecological indicators, 37, 220-228.

MAZEROLLE, M. J. 2003. Detrimental effects of peat mining on amphibian abundance and species richness in bogs. Biological Conservation, 113, 215-223.

MCLOUGHLIN, D., BROWNE, A. & SULLIVAN, C. A. The delivery of ecosystem services through results-based agri-environment payment schemes (RBPS): three Irish case studies. Biology and Environment: Proceedings of the Royal Irish Academy, 2020. JSTOR, 91-106.

MCNIFF, J. 2014. Writing and doing action research, Sage.

MCVEIGH, P., SOTTOCORNOLA, M., FOLEY, N., LEAHY, P. & KIELY, G. 2014. Meteorological and functional response partitioning to explain interannual variability of CO2 exchange at an Irish Atlantic blanket bog. Agricultural and Forest Meteorology, 194, 8-19.

MENBERU, M. W., MARTTILA, H., TAHVANAINEN, T., KOTIAHO, J. S., HOKKANEN, R., KLØVE, B. & RONKANEN, A.-K. 2017. Changes in Pore Water Quality After Peatland Restoration: Assessment of a

Large-Scale, Replicated Before-After-Control-Impact Study in Finland. Water Resources Research, 53, 8327-8343.

MILCU, A. I., HANSPACH, J., ABSON, D. & FISCHER, J. 2013. Cultural ecosystem services: a literature review and prospects for future research. Ecology and society, 18.

MINAYEVA, T. Y., BRAGG, O. & SIRIN, A. 2017. Towards ecosystem-based restoration of peatland biodiversity. Mires and Peat, 19, 1-36.

MOCKLER, E. M., DEAKIN, J., ARCHBOLD, M., GILL, L., DALY, D. & BRUEN, M. 2017. Sources of nitrogen and phosphorus emissions to Irish rivers and coastal waters: Estimates from a nutrient load apportionment framework. Science of The Total Environment, 601, 326-339.

MOHAMMADIGHAVAM, S., HEIDERSCHEIDT, E., MARTTILA, H. & KLØVE, B. 2016. Optimization of Gravity-Driven Hydraulic Flocculators to Treat Peat Extraction Runoff Water. Journal of Irrigation and Drainage Engineering, 142, 04015045.

MONTEITH, D. T., STODDARD, J. L., EVANS, C. D., DE WIT, H. A., FORSIUS, M., HOGASEN, T., WILANDER, A., SKJELKVALE, B. L., JEFFRIES, D. S., VUORENMAA, J., KELLER, B., KOPACEK, J. & VESELY, J. 2007. Dissolved organic carbon trends resulting from changes in atmospheric deposition chemistry. Nature, 450, 537-540.

MOORE, P. D. & BELLAMY, D. J. 1974. Peatlands, London, Elek Science.

MOORE, T. 1987. A PRELIMINARY STUDY OF THE EFFECTS OF DRAINAGE AND HARVESTING ON WATER QUALITY IN OMBROTROPHIC BOGS NEAR SEPT-ILES, QUEBEC1. JAWRA Journal of the American Water Resources Association, 23, 785-791.

MOORKENS, E. A. 2006. Monitoring Populations of the Freshwater Pearl Mussel. Baseline survey of the Eske River cSAC, County Donegal. Report for the National Parks and Wildlife Service. Dublin.

MÜLLER, D., WARNEKE, T., RIXEN, T., MÜLLER, M., JAMAHARI, S., DENIS, N., MUJAHID, A. & NOTHOLT, J. 2015. Lateral carbon fluxes and CO2 outgassing from a tropical peat-draining river. Biogeosciences, 12, 5967-5979.

MÜLLER, S. D., RICHARD, P. J. H. & LAROUCHE, A. C. 2003. Holocene development of a peatland (southern Québec): a spatio-temporal reconstruction based on pachymetry, sedimentology, microfossils and macrofossils. The Holocene, 13, 649-664.

MUSTAMO, P., MALJANEN, M., HYVÄRINEN, M., RONKANEN, A.-K. & KLØVE, B. 2016. Respiration and emissions of methane and nitrous oxide from a boreal peatland complex comprising different land-use types. Boreal Environment Research, 21, 405-426.

NEDWELL, D. B. & WATSON, A. 1995. CH4 production, oxidation and emission in a UK ombrotrophic peat bog: influence of SO2-4 from acid rain. Soil Biology and Biochemistry, 27, 893 - 903.

NEGASSA, W., MICHALIK, D., KLYSUBUN, W. & LEINWEBER, P. 2020. Phosphorus Speciation in Long-Term Drained and Rewetted Peatlands of Northern Germany. Soil Systems, 4, 11.

NICHOLS, J. E. & PETEET, D. M. 2019. Rapid expansion of northern peatlands and doubled estimate of carbon storage. Nature Geoscience.

NIEMINEN, M., HÖKKÄ, H., LAIHO, R., JUUTINEN, A., AHTIKOSKI, A., PEARSON, M., KOJOLA, S., SARKKOLA, S., LAUNIAINEN, S., VALKONEN, S., PENTTILÄ, T., LOHILA, A., SAARINEN, M., HAAHTI, K.,

MÄKIPÄÄ, R., MIETTINEN, J. & OLLIKAINEN, M. 2018. Could continuous cover forestry be an economically and environmentally feasible management option on drained boreal peatlands? Forest Ecology and Management, 424, 78-84.

NIEMINEN, M., KOSKINEN, M., SARKKOLA, S., LAURÉN, A., KAILA, A., KIIKKILÄ, O., NIEMINEN, T. M. & UKONMAANAHO, L. 2015. Dissolved organic carbon export from harvested peatland forests with differing site characteristics. Water, Air, & Soil Pollution, 226, 181.

NIEMINEN, M., SARKKOLA, S., TOLVANEN, A., TERVAHAUTA, A., SAARIMAA, M. & SALLANTAUS, T. 2020. Water quality management dilemma: Increased nutrient, carbon, and heavy metal exports from forestry-drained peatlands restored for use as wetland buffer areas. Forest Ecology and Management, 465, 118089.

NILSSON, M., SAGERFORS, J., BUFFAM, I., LAUDON, H., ERIKSSON, T., GRELLE, A., KLEMEDTSSON, L., WESLIEN, P. E. R. & LINDROTH, A. 2008. Contemporary carbon accumulation in a boreal oligotrophic minerogenic mire – a significant sink after accounting for all C-fluxes. Global Change Biology, 14, 2317-2332.

NPWS 2015a. Managing Ireland's Peatlands: A National Peatlands Strategy 2015.

NPWS 2015b. National Peatlands Strategy. Dublin, Ireland: National Parks and Wildlife Service.

NPWS 2019. Article 17 Habitats Conservation Assessments 2019. 2.

NUGENT, K. A., STRACHAN, I. B., STRACK, M., ROULET, N. T. & ROCHEFORT, L. 2018. Multi-year net ecosystem carbon balance of a restored peatland reveals a return to carbon sink. Global Change Biology, doi:10.1111/gcb.14449.

O'DRISCOLL, C., LEDESMA, J. L. J., COLL, J., MURNANE, J. G., NOLAN, P., MOCKLER, E. M., FUTTER, M. N. & XIAO, L. W. 2018a. Minimal climate change impacts on natural organic matter forecasted for a potable water supply in Ireland. Science of The Total Environment, 630, 869-877.

O'DRISCOLL, C., O'CONNOR, M., ASAM, Z.-U.-Z., DE EYTO, E., BROWN, L. E. & XIAO, L. 2016. Forest clearfelling effects on dissolved oxygen and metabolism in peatland streams. Journal of Environmental Management, 166, 250-259.

O'DRISCOLL, C., SHEAHAN, J., RENOU-WILSON, F., CROOT, P., PILLA, F., MISSTEAR, B. & XIAO, L. 2018b. National scale assessment of total trihalomethanes in Irish drinking water. J Environ Manage, 212, 131-141.

O’DRISCOLL, C., O’CONNOR, M., DE EYTO, E., POOLE, R., RODGERS, M., ZHAN, X., NIEMINEN, M. & XIAO, L. 2014a. Whole-tree harvesting and grass seeding as potential mitigation methods for phosphorus export in peatland catchments. Forest Ecology and Management, 319, 176-185.

O’DRISCOLL, C., O’CONNOR, M., DE EYTO, E., RODGERS, M. & XIAO, L. 2014b. Creation and functioning of a buffer zone in a blanket peat forested catchment. Ecological engineering, 62, 83-92.

O’DRISCOLL, C., RODGERS, M., O’CONNOR, M., ASAM, Z.-U.-Z., DE EYTO, E., POOLE, R. & XIAO, L. 2011. A Potential Solution to Mitigate Phosphorus Release Following Clearfelling in Peatland Forest Catchments. Water, Air, & Soil Pollution, 221, 1-11.

OECD 2015. OECD Principles on Water Governance.

OJANEN, P., MINKKINEN, K., ALM, J. & PENTTILÄ, T. 2010. Soil–atmosphere CO2, CH4 and N2O fluxes in boreal forestry-drained peatlands. Forest Ecology and Management, 260, 411-421.

OVENDEN, L. 1990. Peat accumulation in Northern Wetlands. Quaternary Research, 33, 377-386.

PAGE, S. E. & BAIRD, A. J. 2016. Peatlands and Global Change: Response and Resilience. Annual Review of Environment and Resources, 41, 35-57.

PAGE, S. E., RIELEY, J. O. & BANKS, C. J. 2011. Global and regional importance of the tropical peatland carbon pool. Global Change Biology, 17, 798-818, doi: 10.1111/j.1365-2486.2010.02279.x.

PALATINSZKY, M., HERBOLD, C., JEHMLICH, N., POGODA, M., HAN, P., VON BERGEN, M., LAGKOUVARDOS, I., KARST, S. M., GALUSHKO, A., KOCH, H., BERRY, D., DAIMS, H. & WAGNER, M. 2015. Cyanate as an energy source for nitrifiers. Nature, 524, 105-108.

PALVIAINEN, M., FINÉR, L., KURKA, A.-M., MANNERKOSKI, H., PIIRAINEN, S. & STARR, M. 2004. Release of potassium, calcium, iron and aluminium from Norway spruce, Scots pine and silver birch logging residues. Plant and Soil, 259, 123-136.

PARISH, F., SIRIN, A., CHARMAN, D., JOOSTEN, H., MINAEVA, T. Y. & SILVIUS, M. 2008. Assessment on peatlands, biodiversity and climate change.

PARKER, N., NAUMANN, E., MEDCALF, K., HAINES-YOUNG, R., POTSCHIN, M., KRETSCH, C., PARKER, J. & BURKHARD, B. 2016. National ecosystem and ecosystem service mapping pilot for a suite of prioritised services. Irish Wildlife Manuals.

PARKHILL, K. L. & GULLIVER, J. S. 2002. Effect of inorganic sediment on whole-stream productivity. Hydrobiologia, 472, 5-17.

PEACOCK, M., RIDLEY, L. M., EVANS, C. D. & GAUCI, V. 2017. Management effects on greenhouse gas dynamics in fen ditches. Science of The Total Environment, 578, 601-612.

POSTILA, H., SAUKKORIIPI, J., HEIKKINEN, K., KARJALAINEN, S. M., KUOPPALA, M., MARTTILA, H. & KLØVE, B. 2014. Can treatment wetlands be constructed on drained peatlands for efficient purification of peat extraction runoff? Geoderma, 228-229, 33-43.

PRICE, J. 1997. Soil moisture, water tension, and water table relationships in a managed cutover bog. Journal of hydrology, 202, 21-32.

PRIEDE, A., MEŽAKA, A., DOBKEVIČA, L. & GRĪNBERGA, L. 2016. Spontaneous revegetation of cutaway fens: can it result in valuable habitats? Mires & Peat, 18.

PSCHENYCKYJ, C. M., CLARK, J. M., SHAW, L. J., GRIFFITHS, R. I. & EVANS, C. D. 2020. Effects of acidity on dissolved organic carbon in organic soil extracts, pore water and surface litters. Science of The Total Environment, 703, 135585.

QASSIM, S. M., DIXON, S. D., ROWSON, J. G., WORRALL, F., EVANS, M. G. & BONN, A. 2014. A 5-year study of the impact of peatland revegetation upon DOC concentrations. Journal of Hydrology, 519, 3578-3590.

RAMCHUNDER, S. J., BROWN, L. E. & HOLDEN, J. 2009. Environmental effects of drainage, drain-blocking and prescribed vegetation burning in UK upland peatlands. Progress in Physical Geography: Earth and Environment, 33, 49-79.

RAMCHUNDER, S. J., BROWN, L. E. & HOLDEN, J. 2012. Catchment-scale peatland restoration benefits stream ecosystem biodiversity. Journal of Applied Ecology, 49, 182-191.

RATHWELL, K. J. & PETERSON, G. D. 2012. Connecting Social Networks with Ecosystem Services for Watershed Governance: a Social-Ecological Network Perspective Highlights the Critical Role of Bridging Organizations. Ecology and Society, 17.

REGAN, S., SWENSON, M. M., O'CONNOR, M. & GILL, A. L. 2020. Ecoydrology, Greenhouse Gas Dynamics and Restoration Guildlines for Degraded Raised Bogs. EPA Research Report No 342. In: AGENCY, E. P. (ed.). Johnstown Castle, Co. Wexford, Ireland.

REGINA, K., NYKÄNEN, H., SILVOLA, J. & MARTIKAINEN, P. J. 1996. Fluxes of nitrous oxide from boreal peatlands as affected by peatland type, water table level and nitrification capacity. Biogeochemistry, 35, 401-418.

REGINA, K., SILVOLA, J. & MARTIKAINEN, P. J. 1999. Short-term effects of changing water table on N2O fluxes from peat monoliths from natural and drained boreal peatlands. Global Change Biology, 5, 183-189.

RENOU-WILSON, F. 2018. Peatlands. In: CREAMER, R. & O'SULLIVAN, L. (eds.) The Soils of Ireland. Cham: Springer International Publishing.

RENOU-WILSON, F., BARRY, C., MÜLLER, C. & WILSON, D. 2014. The impacts of drainage, nutrient status and management practice on the full carbon balance of grasslands on organic soils in a maritime temperate zone. Biogeosciences, 11, 4361-4379.

RENOU-WILSON, F., BOLGER, T., BULLOCK, C., CONVERY, F., CURRY, J., WARD, S., WILSON, D. & MÜLLER, C. 2011. BOGLAND: Sustainable management of Peatlands in Ireland. STRIVE Report Series, 181.

RENOU-WILSON, F. & FARRELL, E. P. 2007. Phosphorus in surface runoff and soil water following fertilization of afforested cutaway peatlands. Boreal environment research, 12.

RENOU-WILSON, F., KEANE, M., MCNALLY, G., O'SULLIVAN, J. & FARRELL, E. P. 2008. BOGFOR Programme - Final Report: A research programme to develop a forest resource on industrial cutaway peatlands in the Irish midlands, Dublin, Coford.

RENOU-WILSON, F., MOSER, G., FALLON, D., FARRELL, C. A., MÜLLER, C. & WILSON, D. 2019. Rewetting degraded peatlands for climate and biodiversity benefits: Results from two raised bogs. Ecological Engineering, 127, 547-560.

RENOU-WILSON, F., MÜLLER, C., MOSER, G. & WILSON, D. 2016. To graze or not to graze? Four years GHG balances and vegetation composition from a drained and a rewetted organic soil under grassland. Agriculture, Ecosystem and the Environment, 222, 156-170.

RENOU-WILSON, F. & WILSON, D. 2018. Vulnerability Assessment of Peatlands: Exploration of Impacts and Adaptation Options in Relation to Climate Change and Extreme Events (VAPOR). EPA Climate Research Report No.

RENOU, F., JONES, S. & FARRELL, E. 2000. Leaching of phosphorus fertilizer applied on cutaway peatland forests recently established in central Ireland. Sustaining our peatlands, 2, 984-990.

REUMER, M., HARNISZ, M., LEE, H. J., REIM, A., GRUNERT, O., PUTKINEN, A., FRITZE, H., BODELIER, P. L. E. & HO, A. 2018. Impact of Peat Mining and Restoration on Methane Turnover Potential and

Methane-Cycling Microorganisms in a Northern Bog. Applied and Environmental Microbiology, 84, e02218-17.

RICHARDSON, C. J. 1983. Pocosins: Vanishing Wastelands or Valuable Wetlands? BioScience, 33, 626-633.

RIGNEY, C., WILSON, D., RENOU-WILSON, F., MUELLER, C., MOSER, G. & BYRNE, K. A. 2018. Greenhouse gas emissions from two rewetted peatlands previously managed for forestry.

RINNE, J., TUOVINEN, J.-P., KLEMEDTSSON, L., AURELA, M., HOLST, J., LOHILA, A., WESLIEN, P., VESTIN, P., ŁAKOMIEC, P., PEICHL, M., TUITTILA, E.-S., HEISKANEN, L., LAURILA, T., LI, X., ALEKSEYCHIK, P., MAMMARELLA, I., STRÖM, L., CRILL, P. & NILSSON, M. B. 2020. Effect of the 2018 European drought on methane and carbon dioxide exchange of northern mire ecosystems. Philosophical Transactions of the Royal Society B: Biological Sciences, 375, 20190517.

RITSON, J. P., BELL, M., BRAZIER, R. E., GRAND-CLEMENT, E., GRAHAM, N. J. D., FREEMAN, C., SMITH, D., TEMPLETON, M. R. & CLARK, J. M. 2016. Managing peatland vegetation for drinking water treatment. Scientific Reports, 6, 9.

ROBINSON, M. 1985. Hydrological effects of moorland gripping: a re-appraisal of the Moor House Research. J. Environ. Manage.;(United States), 21.

RODGERS, M., O'CONNOR, M., HEALY, M. G., O'DRISCOLL, C., ASAM, Z.-U.-Z., NIEMINEN, M., POOLE, R., MÜLLER, M. & XIAO, L. 2010. Phosphorus release from forest harvesting on an upland blanket peat catchment. Forest Ecology and Management, 260, 2241-2248.

RONKANEN, A.-K., PALMER, K., KAIKKONEN, I., KHAN, U., HEIDERSCHEIDT, E. & POSTILA, H. Nitrogen removal efficiency and wintertime hydraulics in mine peatlands. Proceedings 13th International Mine Water Association Congress, 2017. 1397.

ROWE, E. C., TIPPING, E., POSCH, M., OULEHLE, F., COOPER, D. M., JONES, T. G., BURDEN, A., HALL, J. & EVANS, C. D. 2014. Predicting nitrogen and acidity effects on long-term dynamics of dissolved organic matter. Environmental Pollution, 184, 271-282.

ROWLANDS, R. & FEEHAN, J. 2000. The ecological future of industrially milled cutaway peatlands in Ireland. Aspects of Applied Biology, 263-270.

ROWSON, J. G., GIBSON, H. S., WORRALL, F., OSTLE, N., BURT, T. P. & ADAMSON, J. K. 2010. The complete carbon budget of a drained peat catchment. Soil Use and Management, 26, 261-273.

RUBOL, S., SILVER, W. L. & BELLIN, A. 2012. Hydrologic control on redox and nitrogen dynamics in a peatland soil. Science of The Total Environment, 432, 37-46.

RUSSOW, R., TAUCHNITZ, N., SPOTT, O., MOTHES, S., BERNSDORF, S. & MEISSNER, R. 2013. Nitrate turnover in a peat soil under drained and rewetted conditions: results from a [15N]nitrate–bromide double-tracer study. Isotopes in Environmental and Health Studies, 49, 438-453.

RYDER, E., DE EYTO, E., DILLANE, M., POOLE, R. & JENNINGS, E. 2014. Identifying the role of environmental drivers in organic carbon export from a forested peat catchment. Science of the total environment, 490, 28-36.

RYDIN, H. & JEGLUM, J. K. 2013. The biology of peatlands. Second Edition, Oxford university press.

RYFIELD, F., CABANA, D., BRANNIGAN, J. & CROWE, T. 2019. Conceptualizing 'sense of place'in cultural ecosystem services: A framework for interdisciplinary research. Ecosystem Services, 36, 100907.

SAARELA, T., LAFDANI, E. K., LAURÉN, A., PUMPANEN, J. & PALVIAINEN, M. 2020. Biochar as adsorbent in purification of clear-cut forest runoff water: adsorption rate and adsorption capacity. Biochar.

SAARNIO, S., ALM, J., SILVOLA, J., LOHILA, A., NYKÄNEN, H. & MARTIKAINEN, P. J. 1997. Seasonal variation in CH4 emissions and production and oxidation potentials at microsites on an oligotrophic pine fen. Oecologia, 110, 414 - 422.

SAARNIO, S., MORERO, M., SHURPALI, N. J., TUITTILA, E.-S., MÄKILÄ, M. & ALM, J. 2007. Annual CO2 and CH4 fluxes of pristine boreal mires as a background for the lifecycle analyses of peat energy. Boreal Environment Research, 12, 101-113.

SALM, J.-O., MADDISON, M., TAMMIK, S., SOOSAAR, K., TRUU, J. & MANDER, Ü. 2012. Emissions of CO2, CH4 and N2O from undisturbed, drained and mined peatlands in Estonia. Hydrobiologia, 692, 41-55.

SAMSON-DÔ, M. & ST-HILAIRE, A. 2018. Characterizing and modelling the trapping efficiency of sedimentation basins downstream of harvested peat bog. Canadian Journal of Civil Engineering, 45, 478-488.

SARUKHÁN, J., WHYTE, A., HASSAN, R., SCHOLES, R., ASH, N., CARPENTER, S., PINGALI, P., BENNETT, E., ZUREK, M. & CHOPRA, K. 2005. Millenium ecosystem assessment: Ecosystems and human well-being.

SAUNOIS, M., STAVERT, A. R., POULTER, B., BOUSQUET, P., CANADELL, J. G., JACKSON, R. B., RAYMOND, P. A., DLUGOKENCKY, E. J., HOUWELING, S., PATRA, P. K., CIAIS, P., ARORA, V. K., BASTVIKEN, D., BERGAMASCHI, P., BLAKE, D. R., BRAILSFORD, G., BRUHWILER, L., CARLSON, K. M., CARROL, M., CASTALDI, S., CHANDRA, N., CREVOISIER, C., CRILL, P. M., COVEY, K., CURRY, C. L., ETIOPE, G., FRANKENBERG, C., GEDNEY, N., HEGGLIN, M. I., HÖGLUND-ISAKSSON, L., HUGELIUS, G., ISHIZAWA, M., ITO, A., JANSSENS-MAENHOUT, G., JENSEN, K. M., JOOS, F., KLEINEN, T., KRUMMEL, P. B., LANGENFELDS, R. L., LARUELLE, G. G., LIU, L., MACHIDA, T., MAKSYUTOV, S., MCDONALD, K. C., MCNORTON, J., MILLER, P. A., MELTON, J. R., MORINO, I., MÜLLER, J., MURGUIA-FLORES, F., NAIK, V., NIWA, Y., NOCE, S., O'DOHERTY, S., PARKER, R. J., PENG, C., PENG, S., PETERS, G. P., PRIGENT, C., PRINN, R., RAMONET, M., REGNIER, P., RILEY, W. J., ROSENTRETER, J. A., SEGERS, A., SIMPSON, I. J., SHI, H., SMITH, S. J., STEELE, L. P., THORNTON, B. F., TIAN, H., TOHJIMA, Y., TUBIELLO, F. N., TSURUTA, A., VIOVY, N., VOULGARAKIS, A., WEBER, T. S., VAN WEELE, M., VAN DER WERF, G. R., WEISS, R. F., WORTHY, D., WUNCH, D., YIN, Y., YOSHIDA, Y., ZHANG, W., ZHANG, Z., ZHAO, Y., ZHENG, B., ZHU, Q., ZHU, Q. & ZHUANG, Q. 2020. The Global Methane Budget 2000–2017. Earth Syst. Sci. Data, 12, 1561-1623.

SAWICKA, K., ROWE, E. C., EVANS, C. D., MONTEITH, D. T., E.I.VANGUELOVA, WADE, A. J. & J.M.CLARK 2017. Modelling impacts of atmospheric deposition and temperature on long-term DOC trends. Science of The Total Environment, 578, 323-336.

SCHOLTE, S. S., TODOROVA, M., VAN TEEFFELEN, A. J. & VERBURG, P. H. 2016. Public support for wetland restoration: what is the link with ecosystem service values? Wetlands, 36, 467-481.

SCHOUTEN, M. G. 2002. Conservation and restoration of raised bogs: geological, hydrological and ecological studies, The Government Stationary Office.

SCHRÖTER, M., BAŞAK, E., CHRISTIE, M., CHURCH, A., KEUNE, H., OSIPOVA, E., OTEROS-ROZAS, E., SIEVERS-GLOTZBACH, S., VAN OUDENHOVEN, A. P. & BALVANERA, P. 2020. Indicators for relational values of nature's contributions to good quality of life: the IPBES approach for Europe and Central Asia. Ecosystems and People, 16, 50-69.

SEPP, M., KÕIV, T., NÕGES, P. & NÕGES, T. 2018. Do organic matter metrics included in lake surveillance monitoring in Europe provide a broad picture of brownification and enrichment with oxygen consuming substances? Science of The Total Environment, 610-611, 1288-1297.

SHANTZ, M. & PRICE, J. 2006. Hydrological changes following restoration of the Bois-des-Bel Peatland, Quebec, 1999–2002. Journal of Hydrology, 331, 543-553.

SHURPALI, N. J. & VERMA, S. B. 1998. Micrometeorological measurements of methane flux in a Minnesota peatland during two growing seasons. Biogeochemistry, 40, 1-15.

SILVAN, N., LAIHO, R. & VASANDER, H. 2000. Changes in mesofauna abundance in peat soils drained for forestry. Forest Ecology and Management, 133, 127-133.

SILVAN, N., TUITTILA, E.-S., KITUNEN, V., VASANDER, H. & LAINE, J. 2005. Nitrate uptake by Eriophorum vaginatum controls N2O production in a restored peatland. Soil Biology and Biochemistry, 37, 1519-1526.

SILVOLA, J., ALM, J., AHLHOLM, U., NYKÄNEN, H. & MARTIKAINEN, P. J. 1996. CO2 fluxes from peat in boreal mires under varying temperature and moisture conditions. Journal of Ecology, 84, 219-228.

SKJELKVÅLE, B. L., STODDARD, J. L., JEFFRIES, D. S., TØRSETH, K., HØGÅSEN, T., BOWMAN, J., MANNIO, J., MONTEITH, D. T., MOSELLO, R., ROGORA, M., RZYCHON, D., VESELY, J., WIETING, J., WILANDER, A. & WORSZTYNOWICZ, A. 2005. Regional scale evidence for improvements in surface water chemistry 1990–2001. Environmental Pollution, 137, 165-176.

SMITH, R., FOY, R. & LENNOX, S. 1997. Increase in soluble reactive phosphorus transport in grassland catchments in response to soil phosphorus accumulation.

STEIN, L. Y. 2015. Cyanate fuels the nitrogen cycle. Nature, 524, 43-44.

STRACK, M., KEITH, A. M. & ZU, B. 2014. Growing season carbon dioxide and methane exchange at a restored peatland on the Western Boreal Plain. Ecological Engineering, 64, 231-239.

STRACK, M., WADDINGTON, J. M. & TUITTILA, E.-S. 2004. Effect of water table drawdown on northern peatland methane dynamics: implications for climate change. Global Biogeochemical Cycles, 18, doi:10.1029/2003GB002209.

SVENSSON, B. H. & SUNDH, I. 1993. Factors affecting methane production in peat soils. Suo, 43, 183-190.

SWENSON, M. M., REGAN, S., BREMMERS, D. T. H., LAWLESS, J., SAUNDERS, M. & GILL, L. W. 2019. Carbon balance of a restored and cutover raised bog: implications for restoration and comparison to global trends. Biogeosciences, 16, 713-731.

TADAKI, M., SINNER, J. & CHAN, K. M. 2017. Making sense of environmental values: a typology of concepts. Ecology and Society, 22.

TANNEBERGER, F., APPULO, L., EWERT, S., LAKNER, S., Ó BROLCHÁIN, N., PETERS, J. & WICHTMANN, W. 2020. The Power of Nature-Based Solutions: How Peatlands Can Help Us to Achieve Key EU Sustainability Objectives. Advanced Sustainable Systems, n/a, 2000146.

TANNEBERGER, F., MOEN, A., JOOSTEN, H. & NILSEN, N. 2017. The peatland map of Europe.

THE LIVING BOG. 2016. Welcome to the Living Bog [Online]. Available: http://raisedbogs.ie/ [Accessed 14/01/2021 2021].

THOMPSON, R. 1802. A Statistical Survey of Co. Meath. Dublin: Graisberry and Campbell.

TIEMEYER, B., FRINGS, J., KAHLE, P., KÖHNE, S. & LENNARTZ, B. 2007. A comprehensive study of nutrient losses, soil properties and groundwater concentrations in a degraded peatland used as an intensive meadow – Implications for re-wetting. Journal of Hydrology, 345, 80-101.

TIERNEY, D., KELLY-QUINN, M. & BRACKEN, J. 1998. The faunal communities of upland streams in the eastern region of Ireland with reference to afforestation impacts. Hydrobiologia, 389, 115.

TOMLINSON, R. W. 2005. Soil carbon stocks and changes in the Republic of Ireland. Journal of Environmental Management, 76, 77-93.

TUHKANEN, S. 1984. A circumboreal system of climatic-phytogeographical regions. Acta Bot. Fennica, 127, 1-50.

TUITTILA, E.-S., VASANDER, H. & LAINE, J. 2000. Impact of rewetting on the vegetation of a cut-away peatland. Applied Vegetation Science, 3, 205-212.

UNCEEA 2020. System of Environmental-Economic Accounting— Ecosystem Accounting - Draft for the Global Consultation.

UNITED NATIONS ENVIRONMENT PROGRAM 2019. Resolution Adopted by the United Nations Environment Assembly on 15 March 2019. 4-16 Conservation and Sustainable Management of Peatland.

UNIVERSITY OF GREIFSWALD 2012. Paludiculture: Sustainable productive utilisation of rewetted peatlands. www.paludikultur.de.

VÄISÄNEN, R. A. & RAUHALA, P. Succession of land bird communities on large areas of peatland drained for forestry. Annales Zoologici Fennici, 1983. JSTOR, 115-127.

VAN BUSSEL, L. G., DE HAAN, N., REMME, R. P., LOF, M. E. & DE GROOT, R. 2020. Community-based governance: Implications for ecosystem service supply in Berg en Dal, the Netherlands. Ecological Indicators, 117, 106510.

VANGUELOVA, E., CHAPMAN, S., PERKS, M., YAMULKI, S., RANDLE, T., ASHWOOD, F. & MORISON, J. 2018. Afforestation and restocking on peaty soils–new evidence assessment. Report to. CXC (ClimateXChange), Scotland.

WADDINGTON, J. M. & ROULET, N. T. 2000. Carbon balance of a boreal patterned peatland. Global Change Biology, 6, 87- 97.

WALLAGE, Z. E., HOLDEN, J. & MCDONALD, A. T. 2006. Drain blocking: An effective treatment for reducing dissolved organic carbon loss and water discolouration in a drained peatland. Science of The Total Environment, 367, 811-821.

WAWRZYCZEK, J., LINDSAY, R., METZGER, M. J. & QUÉTIER, F. 2018. The ecosystem approach in ecological impact assessment: Lessons learned from windfarm developments on peatlands in Scotland. Environmental Impact Assessment Review, 72, 157-165.

WAYLEN, K. A., VAN DE NOORT, R. & BLACKSTOCK, K. L. 2016. Peatlands and cultural ecosystem services. Peatland Restoration and Ecosystem Services. Science, Policy and Practice, 114.

WHO 2005. Trihalomethanes in Drinking-water (No. WHO/SDE/WSH/05.08/64).

WHO 2009. Water Safety Plan Manual. Step-by-step risk management for drinking water suppliers.

WILLIAMSON, J., EVANS, C., SPEARS, B., PICKARD, A., CHAPMAN, P. J., FEUCHTMAYR, H., LEITH, F. & MONTEITH, D. 2020. Will UK peatland restoration reduce dissolved organic matter concentrations in upland drinking water supplies? Hydrol. Earth Syst. Sci. Discuss., 2020, 1-21.

WILSON, D., BLAIN, D., COUWENBERG, J., EVANS, C., MURDIYARSO, D., PAGE, S., RENOU-WILSON, F., RIELEY, J., SIRIN, A. & STRACK, M. 2016a. Greenhouse gas emission factors associated with rewetting of organic soils. Mires and Peat, 17.

WILSON, D., DIXON, S. D., ARTZ, R. R. E., SMITH, T. E. L., EVANS, C. D., OWEN, H. J. F., ARCHER, E. & RENOU-WILSON, F. 2015. Derivation of greenhouse gas emission factors for peatlands managed for extraction in the Republic of Ireland and the United Kingdom. Biogeosciences, 12, 5291-5308.

WILSON, D., FARRELL, C., FALLON, D., MOSER, G., MULLER, C. & RENOU-WILSON, F. 2016. Multi-year greenhouse gas balances at a rewetted temperate peatland. Global Change Biology, 22, 4080-4095, DOI: 10.1111/gcb.13325.

WILSON, D., MÜLLER, C. & RENOU-WILSON, F. 2013a. Carbon emissions and removals from Irish peatlands: current trends and future mitigation measures. Irish Geography, 46, 1-23.

WILSON, D., TUITTILA, E.-S., ALM, J., LAINE, J., FARRELL, E. P. & BYRNE, K. A. 2007. Carbon dioxide dynamics of a restored maritime peatland. Ecoscience, 14, 71-80.

WILSON, E., SHORT, I. & NI DHUBHAIN, A. 2018. Continuous cover forestry: the rise of transformational silviculture.

WINKLER, M. G. & DEWITT, C. B. 1985. Environmental impacts of peat mining in the United States: documentation for wetland conservation. Environmental conservation, 12, 317-330.

WORRALL, F., ARMSTRONG, A. & HOLDEN, J. 2007a. Short-term impact of peat drain-blocking on water colour, dissolved organic carbon concentration, and water table depth. Journal of Hydrology, 337, 315.

WORRALL, F. & BURT, T. 2005. Predicting the future DOC flux from upland peat catchments. Journal of Hydrology, 300, 126-139.

WORRALL, F., GIBSON, H. S. & BURT, T. P. 2007b. Modelling the impact of drainage and drain-blocking on dissolved organic carbon release from peatlands. Journal of Hydrology, 338, 15-27.

WORRALL, P., PEBERDY, K. J. & MILLETT, M. C. 1997. Constructed wetlands and nature conservation. Water Science and Technology, 35, 205-213.

XU, J., MORRIS, P. J., LIU, J. & HOLDEN, J. 2018. PEATMAP: Refining estimates of global peatland distribution based on a meta-analysis. CATENA, 160, 134-140.

YAVITT, J. B. & KNAPP, A. K. 1995. Methane emission to the atmosphere through emergent cattail (Typha latifolia L.) plants. Tellus, 47B, 521-534.

YU, Z., LOISEL, J., BROSSEAU, D. P., BEILMAN, D. W. & HUNT, S. J. 2010. Global peatland dynamics since the Last Glacial Maximum. Geophysical Research Letters, 37, L13402.

YU, Z. C. 2012. Northern peatland carbon stocks and dynamics: a review. Biogeosciences, 9, 4071-4085.

ZHAO, P., PALVIAINEN, M., KÖSTER, K., BERNINGER, F., BRUCKMAN, V. J. & PUMPANEN, J. 2019. Effects of Biochar on Fluxes and Turnover of Carbon in Boreal Forest Soils. Soil Science Society of America Journal, 83, 126-136.