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RESEARCH ARTICLE

Applying ecosystem accounting to develop a risk register for peatlands and inform restoration targets at catchment scale: a case study from the European region

Catherine A. Farrell[1,2], Lisa Coleman[3], Daniel Norton[4], Mary Kelly-Quinn[3], Stephen Kinsella[4], Carl Obst[5], Mark Eigenraam[5], Cathal O'Donoghue[6], Iseult Sheehy[7], Fiona Smith[7], Jane C. Stout[1]

Combining natural capital accounting tools and ecosystem restoration approaches builds on existing frameworks to track changes in ecosystem stocks and flows of services and benefits as a result of restoration. This approach highlights policy-relevant benefits that arise due to restoration efforts and helps to maximize opportunities for return on investment. Aligning the System of Environmental Economic Accounting–Ecosystem Accounting (SEEA EA) framework with risk assessment tools, we developed a risk register for peatlands in two contrasting catchments in Ireland, based on available information relating to peatland *stocks* (extent and condition) and *flows* (services and benefits), as well as knowledge of pressures. This approach allowed for identification of areas to target peatland restoration, by highlighting the potential to reduce and reverse negative trends in relation to provisioning, regulating, and cultural services, flows relating to non-use values, as well as abiotic flows. We also highlighted ways to reduce and reverse the effects of historical and ongoing pressures through restoration measures, aligning our approach with that outlined in the SER *International Principles and Standards for the Practice of Ecological Restoration*. Building on the synergies between the SEEA EA and the SER Standards is highlighted as a means to develop transdisciplinary collaboration, to assist in setting and achieving targets set out under the UN Decade on Ecosystem Restoration as well as integrating regional policy targets set under the EU Biodiversity Strategy for 2030, and the related EU Habitats and EU Water Framework Directives.

Key words: ecosystem stocks and flows, natural capital accounting, peatlands, Society of Ecological Restoration Standards, System of Environmental Economic Accounting–Ecosystem Accounts

Implications for Practice

- Developing a risk register for flows of peatland services and benefits at catchment scale identifies areas where restoration presents opportunities to maximize return on investment for multiple policy-relevant benefits for climate, water, biodiversity, and people.
- Combining the multidisciplinary tools of ecosystem accounting and risk assessment, this approach assists prioritization of areas for restoration, supporting effective use of competing resources and time.
- Despite limited data availability, the catchment scale approach outlined here can be extended regionally and globally across other ecosystem types.
- Aligning the UN SEEA EA with restoration frameworks such as the SER Standards, presents scope for synergy to set and achieve targets outlined under the UN Decade on Ecosystem Restoration and EU restoration plans.

Introduction

The Role of Ecosystem Restoration

Natural ecosystems are essential to sustainable development, poverty alleviation, and improved human well-being, thereby underpinning the UN Sustainable Development Goals (SDGs) (UN 2019). However, long-term trends in degradation of ecosystems and changes in planetary systems, such as climate regulation, present immediate challenges, and threats to achieving these goals (Steffen et al. 2015; Díaz et al. 2019; IPCC 2021). Repeated calls to address these global issues require both

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[1] Department of Botany, TCD School of Natural Sciences, Trinity College Dublin, Dublin, Ireland
[2] Address correspondence to C. A. Farrell, email farrec23@tcd.ie
[3] School of Biology and Environmental Science, University College Dublin, Dublin, Ireland
[4] Department of Economics, University of Limerick Kemmy Business School, Limerick, Ireland
[5] IDEEA (Institute for Development of Environmental-Economic Accounting) Group, Melbourne, Australia
[6] Department of Geography, National University of Ireland, Galway, Galway, Ireland
[7] Natural Capital Ireland, Dublin, Ireland

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transformational behavior and collaborative approaches across social, environmental, and economic disciplines (Dasgupta 2021). Ecosystem restoration plays a central role, with frameworks such as the *International Principles and Standards for the Practice of Ecological Restoration* developed by the Society of Ecological Restoration (SER) (hereto referred to as the SER Standards), designed to facilitate a systematic approach to restoration (Gann et al. 2019).

Recognizing the integrated challenges of biodiversity loss and climate change, the UN Decade on Restoration (2021–2030) builds on an array of UN multilateral agreements, with the aim of supporting and scaling up efforts to prevent, halt, and reverse the degradation of ecosystems worldwide, while also aiming to raise awareness of the importance of successful ecosystem restoration in terms of the broader suite of SDGs (UN 2019). The UN Decade on Restoration is reflected in the European Union (EU) Biodiversity Strategy for 2030 (a core delivery mechanism of the European Green Deal) and legally binding nature restoration targets proposed at the end of 2021 (Vysna et al. 2021).

In order to set achievable targets, a number of questions must be answered such as what should be restored and why, what can be restored and where, how can restoration targets be achieved and over what time frame(s), and who will resource and ensure targets are met and/or adjusted over time. In this paper, using peatland ecosystems as an example, we outline an approach to identifying, setting, and monitoring ecosystem restoration targets, by combining the interdisciplinary tools of risk assessment with the UN System of Environmental Economic Accounting–Ecosystem Accounting (SEEA EA) (UNSD 2021), along with an understanding of restoration frameworks (Gann et al. 2019).

Ecosystem Accounting to Support Restoration

Developed in the EU context through the Mapping and Assessment of Ecosystem Services (MAES) and Integrated Natural Capital Accounting (INCA) projects, the SEEA EA framework has been highlighted as one of the tools to support the EU nature restoration plan (Vysna et al. 2021). The traditional-economic focused terms *stocks* and *flows* as well as *assets* are used to allow for integration and alignment of the SEEA EA with established accounting frameworks such as the System of National Accounts or SNA, the internationally agreed standard on how to compile measures of economic activity (Eigenraam & Obst 2018). The SEEA EA presents a geospatial approach, whereby ecosystem *stocks* (extent and condition) and *flows* (services and benefits) are recorded and tracked over time, serving to account for nature's contributions to human well-being (Obst 2015; Hein et al. 2020*a*; Farrell et al. 2021*a*). Adopted as a statistical standard by the UN in 2021, trials at national (Hein et al. 2020*b*) and catchment scale (Farrell et al. 2021*a*, 2021*b*) have demonstrated that the SEEA EA framework facilitates an integrated data platform and a means to incorporate natural capital (as per the definition by the Capitals Coalition, which includes additional aspects of the natural systems such as soils and mineral aggregates alongside ecosystems) into existing ways of public and business decision-making at all levels (Bateman & Mace 2020; Hein et al. 2020*a*; Farrell et al. 2021*a*).

SEEA EA accounts, and broader natural capital accounts, can be used on their own or incorporated into other analyses, such as cost–benefit analysis, economic impact analysis, and other causal modeling techniques, providing the level of context necessary for integrated decision-making (Bateman & Mace 2020). Equally, the accounts can highlight areas that require restoration by identifying ecosystems that are declining, or have declined already, in extent and/or condition (Farrell et al. 2021*c*), serving as a readymade integrated monitoring tool to track changes in both ecosystem stocks and flows as a result of restoration measures (UNSD 2021; Vysna et al. 2021).

Ecosystem accounts developed for an array of ecosystems at EU level show that the condition of most ecosystems is unfavorable-bad (Maes et al. 2020). Favorable conservation status, as defined under the EU Habitats Directive, infers that habitats must have sufficient area and quality to ensure maintenance into the medium to long term, along with favorable future prospects in the face of pressures and threats (NPWS 2019). Wetlands, in particular, show a continued deteriorating trend across the EU region, their critical state requiring transformative changes at all levels to ensure further losses are averted (Maes et al. 2020). Peatlands are wetlands characterized by complex interactions between water, peat soil, biodiversity, and people. Ecosystem accounts developed at national scale for peatlands by the United Kingdom (ONS 2019) and the Netherlands (Hein et al. 2020*b*) have focused largely on the potential benefits to be gained from restoration, highlighting that conservation and restoration underpins and strengthens the resilience of peatlands (van der Velde et al. 2021), delivering a range of cobenefits for climate, water, and biodiversity (Maes et al. 2020).

Peatland Ecosystems: Threatened Natural Capital

Covering less than 3% of the global land surface, peatlands represent significant global carbon stores, substantially more than the carbon stock in the entire forest biomass globally (Joosten et al. 2016), which cover 10 times the area (30%) (Köhl et al. 2015). Apart from being long-term carbon stores, healthy peatlands provide global climate and water regulation services (Bonn et al. 2016). Widely recognized as important areas for biodiversity, peatlands are significant socio-cultural landscapes that underpin the livelihoods of communities across the globe, thereby comprising globally important natural capital (Bonn et al. 2016). Drainage and extraction of peat degrades peatland condition and reverses the flow of ecosystem services (Evans et al. 2014; Renou-Wilson et al. 2019). For example, degradation switches peatlands from being carbon stores and sinks to carbon sources, and estimates indicate that degraded peatlands will contribute 8% of the global anthropogenic CO_2 emissions by 2050 (Urák et al. 2017). In addition, degradation results in reduced water quality, changes in regulation of water flow, and loss of biodiversity (Martin-Ortega et al. 2014, 2021).

Peatland restoration, and wetland restoration in general, is viewed as a cost-effective nature-based solution, assisting in the conservation of wetland habitats, while also serving to reduce negative trends in ecosystem services (Bonn et al. 2016; Maes et al. 2020). Ireland is a global hotspot for peatlands, with over

20% of the national territory covered by peatland or peat soils (Connolly & Holden 2009). Conversion of peatlands to other land uses (agriculture, conifer plantation, and/or peat extraction) ongoing since the eighteenth century has been one of the main pressures resulting in drainage and loss of typical peatland vegetation. Combined with additional pressures, including overgrazing, burning, recreational use, and development for renewable energy infrastructure, these activities have resulted in the overall degradation of more than 80% of Irish peatland ecosystems (Connolly 2019). All peatland types listed under Annex I of the EU Habitats Directive are considered to be of unfavorable-bad conservation status since the start of reporting in 2007 (NPWS 2019).

One of the main goals of the UN Decade on Ecosystem Restoration is to promote the recovery of resilient natural ecosystems, better able to withstand the effects of global climate change (UN 2019). This underlines the urgency to restore peatlands as their ongoing deterioration is likely to be exacerbated by climate change while at the same time, degraded peatlands will likely contribute further to climate warming with further negative impacts on water and biodiversity, and other hazards such as fire and landslides (Renou-Wilson & Wilson 2018).

Developing a Risk Register of Flows for Peatlands

Clearly, decision-making in relation to peatland use and restoration resonates across policy areas relating to climate, water and biodiversity, and sustainable livelihoods (Bonn et al. 2016). Using the SEEA EA framework to build an understanding of past and present extent and condition of peatlands, in combination with knowledge of trends relating to pressures and constraints, can highlight those peatlands, including those outside of nature conservation networks, at risk of not achieving conservation and restoration targets (Farrell et al. 2021*b*, 2021*c*). Similarly, combining this assessment of stocks with knowledge of peatland flows can inform the potential risk of declines in peatland ecosystem services and benefits, thereby forming the basis for a risk register for peatland flows. The same rationale formed the basis for Mace et al. (2015) to develop a natural capital risk register for eight broad habitat types in the United Kingdom (including moors and heathlands) by highlighting natural assets/stocks whose declining extent and deteriorating condition places continued delivery of flows at risk. Widely used within the business community, a risk register is one of the tools of risk management, serving to inform selection and implementation of measures to minimize or avoid the risk of losses (such as decline or reversal of flows), as well as to maximize the realization of opportunities, such as, in the context of peatland ecosystems, investment in restoration to deliver returns in terms of improved stocks and flows.

In this paper, we outline an approach using the SEEA EA framework to develop a risk register of peatland flows in Ireland. We present this as a useful means to identify and monitor ecosystem restoration targets based on understanding the relationships between peatland ecosystem stocks (extent and condition) and flows (services and benefits), thereby allowing for trade-offs in decision-making to be made more transparent based on available, relevant information. The catchment was selected as it presents a distinct biophysical landscape unit with well-defined boundaries, forming the basis at which reporting is carried out under the EU Water Framework Directive (WFD) (Farrell et al. 2021*b*, 2021*c*). We present our findings as follows:

1. We outline ecosystem services for two contrasting catchments in Ireland, using published ecosystem accounts relating to peatland extent and condition developed under the SEEA EA framework as the basis for our assessment (Farrell et al. 2021*b*, 2021*c*).
2. Aligning the SEEA EA accounts with knowledge of pressures and combining elements of the approach developed by Mace et al. (2015), we outline a risk register for peatland flows (services and benefits) in each study catchment, highlighting also potential restoration measures.
3. We outline relevant data gaps, offering some conclusions to facilitate and streamline application of the SEEA EA framework, highlighting synergies with restoration frameworks such as the SER Standards, and the potential for their combined use to set and monitor restoration targets.

Methods

The SEEA EA Accounting Framework

The SEEA EA is a geospatial approach whereby existing data on ecosystem stocks and flows, at a range of scales, are collated with four core accounts (Fig. 1; UNSD 2021). We note that the terms *stocks* and *flows* which are traditionally used in an economic perspective are not commonly applied in ecological restoration. However, they are used explicitly to allow for the outputs of the SEEA EA to be integrated into existing economic accounting methods (Obst et al. 2016; Eigenraam & Obst 2018).

Asset Extent. This relates to the type, range, and extent of ecosystems assets within an accounting area. Ecosystem assets are the ecological entities for which information is sought and about which statistics are ultimately compiled, and the use of national ecosystem typologies, that can be aligned with the IUCN Global Ecosystem Typology (Keith et al. 2020), is recommended as a common system to allow for comparative analysis across study areas (UNSD 2021). For this account, time series data at an appropriate scale for the accounting area outlining the type, range, and extent of ecosystems assets are required (UNSD 2021). The outputs include geo-referenced maps (the scale depending on the spatial unit selected, such as national or catchment level) and an asset register or account (in the form of a table/balance sheet).

Asset Condition. This relates to the quality of the assets outlined in the extent account. The SEEA EA is specific about the definition of ecosystem condition as “the quality of an ecosystem measured in terms of its abiotic and biotic characteristics.” Quality is assessed with respect to ecosystem structure, function, and composition, which combine to underpin the ecological integrity of the ecosystem and, thereby, its capacity to supply

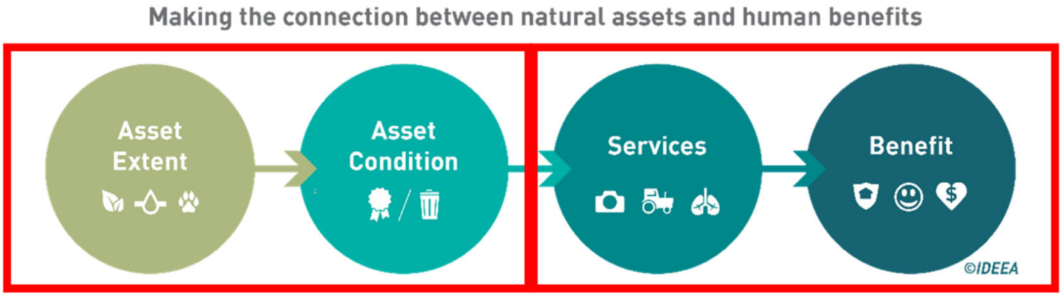


Figure 1. The SEEA EA framework. Four accounts within the SEEA EA framework form the basis of the approach, broken into stocks (natural asset extent and condition) and flows (services and benefits that flow from the natural assets). Source: IDEEA Group.

ecosystem services (UNSD 2021). The SEEA EA outlines a three-stage approach to developing condition accounts, recommending the use of traceable, dynamic ecosystem condition variables, as well as setting reference levels which allow for development of, and aggregation of, condition indicators within and across ecosystem types (UNSD 2021), though few examples beyond the first stage of condition accounting are reported (Farrell et al. 2021*b*, 2021*c*). At this stage of the accounting, maps and tables outlining asset condition are developed, often integrating disparate ancillary datasets relating to policy-relevant pressures. These can infer the use of ecosystems and associated service provision (such as locations of and/or intensity of use) for the next stages of accounting (services and benefits).

Services. This requires the identification of the flows of ecosystem services, whether within the system or as a product of the system. Ecosystem services are defined in the SEEA EA as the contributions of ecosystems to the benefits that are used in economic and other human activity (UNSD 2021). Services may rely on a combination and interaction of multiple ecosystem assets. Mapping services can also integrate data relating to pressures and condition mapping in previous steps, as well as using other relevant geospatial data. While data relating to services can be biophysical, there may also be links to economic datasets.

Benefits. These are defined as the goods and services that are ultimately used and enjoyed by people and society (UNSD 2021) and accounts developed outline what the benefits and who the beneficiaries are. For some services, there is a spatial correlation between potential beneficiaries and service availability, while for others, the spatial link may be more difficult to ascertain. This account can be developed using economic valuation techniques, though this aspect of the SEEA EA is still regarded as experimental (UNSD 2021).

Each step of the accounting requires the gathering, assessment, and integration of relevant datasets. As a consequence, data review and analysis, combined with iterative engagement with data providers, as well as potential end-users, comprise a major part of the process of developing ecosystem accounts. Following from this iterative, interactive learning process, the accounts provide an integrated data platform that can be used to provide information for decisions, each application depending on the perspective of the end-user(s) and the policy focus, usually outlined at the beginning but which can be refined over the course of the accounting process (Eigenraam & Obst 2018; Farrell et al. 2021*b*).

Case Study Accounting Areas

We selected two catchment areas, the Dargle and the Figile, as they have a relatively high cover of peatlands (25 and 36%, respectively) and reflect a subsample of peatland types in Ireland. These include peatlands considered of nature conservation value (Annex I habitat types listed under the EU Habitats Directive) and degraded peatland types. Catchment details are summarized in Table 1. We note there are no data available on fen peatlands. Further, given the limited available data, all other peatland types are aggregated for the purposes of this study.

The Dargle peatlands are dominated by a mosaic of upland blanket bog and wet heathland (Fig. 2). The main pressures relate to the effects of historical turf cutting, overgrazing by sheep during the 1980s, present day recreational walking, along with uncontrolled burning. The Figile peatlands, originally dominated by raised bog complexes pre-1930s, were systematically drained and developed for industrial peat extraction to the present day, with small remnant fragments of raised bog remaining (<1% of the catchment) (Fig. 3). While industrial peat extraction ceased in 2020, domestic turf cutting is widespread in the Figile and ongoing, with all peatlands subject to drainage. Peatlands were previously more extensive in both catchments, with approximately 50% converted to other land cover types including agricultural grassland and commercial forestry prior to 2000.

The condition of peatlands in both catchments is considered bad, based on structure and function being negatively impacted by drainage and bare peat exposure. Given past and ongoing pressures, all peatland types are at risk of not achieving reference condition levels unless active restoration measures are taken (Farrell et al. 2021*c*).

Data Inventory and Assessment

Using relevant datasets available, we applied the process steps as outlined in the SEEA EA (UNSD 2021) to develop extent,

Table 1. Study catchment summary details with outline peatland extent, type, and condition account information developed under the SEEA EA framework (summarized from Farrell et al. 2021*c*).

Catchment Accounts/Datasets	*Dargle*	*Figile*
Ancillary data		
Total catchment area	17,864 ha (178 km^2)	30,143 ha (301 km^2)
National context	Dublin City and north County Wicklow (east Ireland)	Offaly and Kildare (midlands of Ireland)
River system (WFD code)	Avoca-Varty river system (EPA WFD code: 10_5)	Barrow river system (EPA WFD code: 14_3 and EPA WFD code: 14_14)
Peatland area designated for conservation	All peatlands (approximately 3,608 ha) conserved within the EU Natura 2000 network (the network of nature protection areas in the EU)	A small area (approximately 264 ha) of peatlands (0.88% of total area) conserved within nationally designated sites
Total % area of catchment designated for nature conservation	Approximately 25% of total catchment area (of which approximately 20% is peatland habitats)	Approximately 1.4% of total catchment area (approximately 1% is peatland habitats)
Extent account data		
CORINE 2000 peatland classes	23% (Peat bogs, Moors and heathlands)	36% (Peat bogs)
CORINE 2018 peatland classes	25% (included Peat bogs, Moors and heathlands and additional CORINE category Burnt areas)	32% (Peat bogs)
CORINE change product 2000–2018	<−0.5%	<−1%
Peat soil texture (pre-2000 peatland extent)	41%	69%
Peatland types		
All peatland types (based on national typology of Fossitt (2000))	Upland (mountain) blanket bog and wet heathland (near natural and degraded types), patchy fen remnants present	Raised bog; cutaway industrial peatland; domestic cutover; patchy fen remnants present
Extent and types of EU Habitats Directive Annex I peatlands (based on Article 17 data)	20%: active mountain blanket bog and wet heathland	<1%: active and degraded raised bog
Peatland reference condition		
Annex I types	Active blanket bog and wet heathland (Annex I habitats)	Active and degraded raised bog (Annex I habitats)
Cutaway and cutover peatland types	Rewetted, revegetated and environmentally stabilized	Rewetted, revegetated and environmentally stabilized
Peatland condition (all peatland types aggregated)	Bad (declining)	Bad (declining)
Pressures and threats		
EU Habitats Directive Annex I habitats	Historical drainage for turf cutting still active; effects of past overgrazing evident; ongoing peat erosion and uncontrolled burning; ongoing trampling and exposure of bare peat due to recreational use (walking); ongoing conversion to other land use types	Turf cutting active at margins of raised bog habitats; effects of past cutting evident; restoration is required to conserve and restore Annex I habitats
Degraded peatland types	Degraded blanket bog and wet heathland: turf cutting inactive, but drains remain active; no active measures to restore degraded and/or cutover areas	Industrial cutaway: active measures are in planning phase to rehabilitate industrial cutaway. Cutover bog turf cutting likely to continue and may increase/extend to other areas with no licensing obligation to rehabilitate

condition, services, and benefits accounts. A desktop review of available national and catchment level datasets (with particular focus on peatlands data) was combined with stakeholder engagement through focused workshops with relevant data providers and stakeholders, as outlined in Farrell et al. (2021*b*). Datasets for peatland stock assessment, namely their extent and condition, were based on published data outlined in Farrell et al. (2021*c*). The key datasets used for developing SEEA EA peatland flow accounts, namely services and benefits, in the catchment accounting areas, included national scale datasets including Land Parcel Identification System or LPIS (2019 dataset), commonage assessment data, national soil data (peat texture), livestock numbers (CSO data), National Inventory Reporting for greenhouse gas emissions (peatland emission factors), Water Framework Directive datasets (ecological status and pressures data), Landslide vulnerability datasets, EU

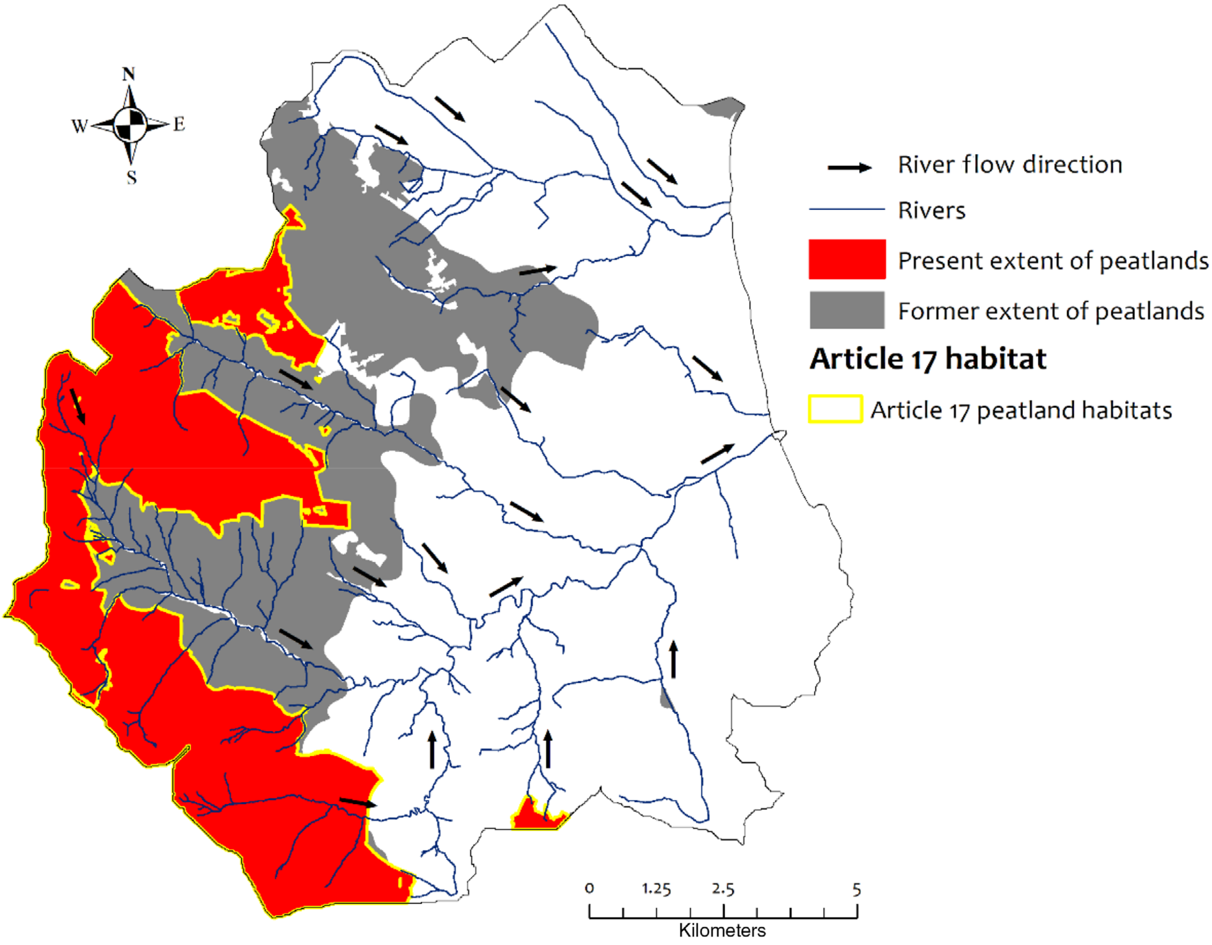


Figure 2. Outline of the Dargle catchment showing the present (red) and former (gray) extent of peatlands. Extent of EU Habitats Directive Annex I (Article 17) peatland habitats is highlighted in yellow.

Habitats Directive data (Article 17 data, designations), datasets developed under the national MAES pilot project, Strava recreational use datasets, peat energy use data (CSO data), and focused catchment data used (relating to industrial peat extraction and education providers) where available and relevant. Use of the data is summarized in Table 2 and described in detail (source, description, and relevance) in Table S1 and Supplement S1.

Building SEEA EA Flow Accounts

Services. Geospatial datasets relating to indicators of service supply and use were reviewed and assessed (Tables 2 & S1). We described in qualitative terms the main ecosystem services provided by peatlands in each catchment, with quantitative estimates based on available data and supporting literature. The services assessed include provisioning (grazing biomass), regulating (climate regulation, water purification, river flood mitigation, landslide mitigation services, and habitat maintenance), and cultural services (recreation and educational) as well as flows relating to non-use values (ecosystem appreciation). Under the SEEA EA framework, inputs of mineral and energy resources and soil resources (excavated), and energy inputs from renewable sources (e.g. solar, wind) are excluded from the scope of ecosystem services but may be recorded as abiotic flows (UNSD 2021). We included peat for energy and wind energy as abiotic flows.

Benefits. Combining available datasets with stakeholder engagement informed the identification of benefits and beneficiaries in each catchment.

Developing a Risk Register for Peatland Flows

We assessed the likelihood of and level of impacts on future flows based on the matrix outlined in Figure 4. Combining information gathered under the SEEA EA framework with elements of the work by Mace et al. (2015), we used the status and trends in peatland stocks as a basis to outline the relationships between peatland stocks and likely flows in each catchment. For example, where a peatland is in bad condition, the flows of services such as carbon sequestration and water retention are reduced. Ongoing pressures may result into continued, and potentially, further reductions. On this basis, incorporating knowledge of

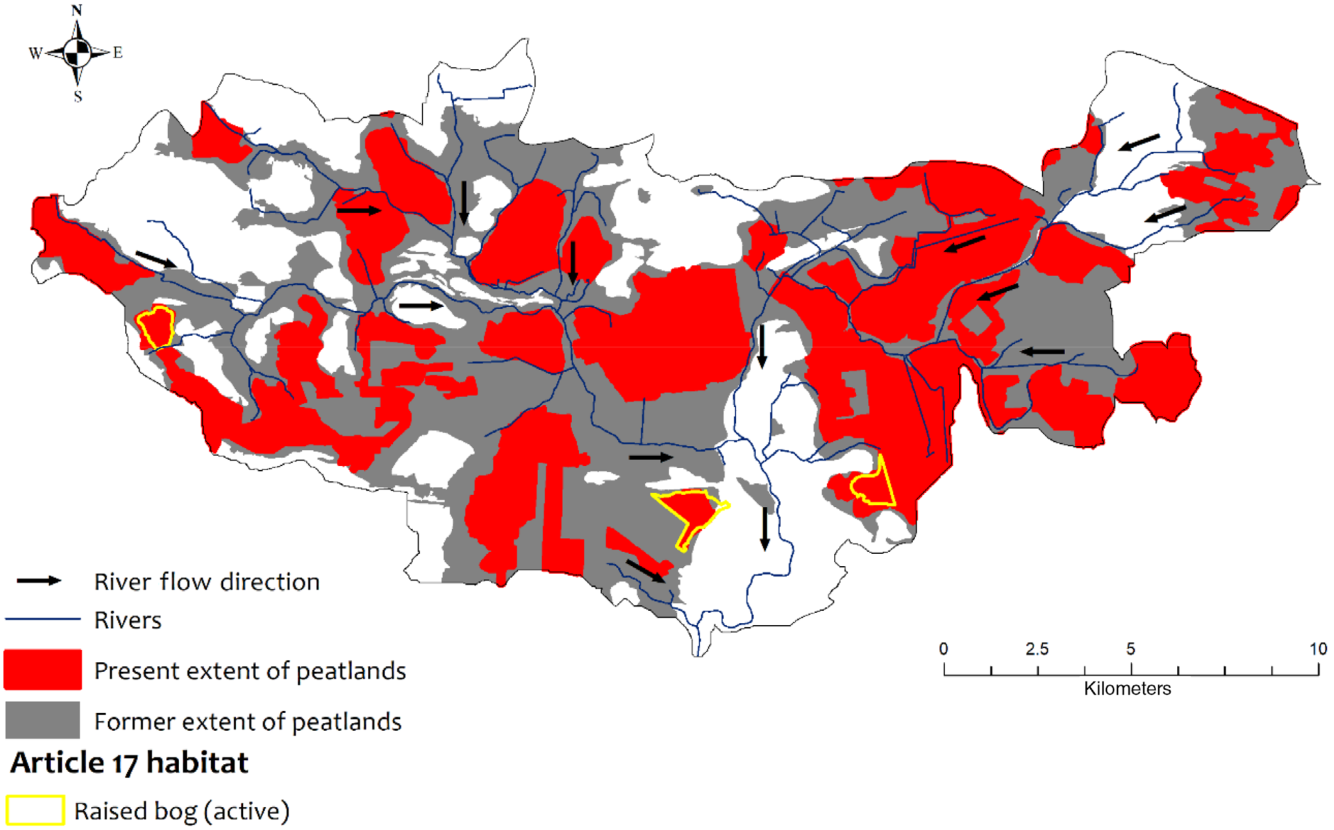


Figure 3. Outline of the Figile catchment showing the present (red) and former (gray) extent of peatlands. Extent of EU Habitats Directive Annex I (Article 17) peatland habitats is highlighted in yellow.

historical and ongoing pressures and threats, we developed a risk register of peatland flows in each catchment. The risk register is color coded (Fig. 4) and based on the RAG (red/amber/green) scoring/risk levels used by Mace et al. (2015). We further aligned each color code with an indicative restorative action to avoid, reduce, and/or mitigate risk, based on based on expert ecological opinion and a review of relevant restorative measures and outcomes on peatlands (Thom et al. 2019). Where peatland flows are coded green, the recommended action is ongoing monitoring to track any likely changes due to trends in other flows; for those coded amber, restorative actions are required to avoid/mitigate levels of and/or likelihood of impacts due to ongoing or increasing pressures. For those coded red, immediate action is deemed necessary to assess and address causes and levels of degradation and inform selection and implementation of appropriate restorative measures.

Results

Peatland Stocks

Extent and Condition. Data supporting the extent and condition accounts for peatlands in both catchments are outlined in Table 1, Figures 2 and 3. All peatlands are considered in bad condition (with a declining trend). The basis for the assessment is outlined in Farrell et al. (2021*c*).

Peatland Flows

An overview of ecosystem services assessed is summarized in Table 2 with supporting information in Supplement S1 and relevant datasets referenced in Table S1.

Provisioning Services. The main provisioning service of relevance was grazing biomass for the Dargle only, where partial areas of peatland commonages continue to be used for grazing sheep in 2019 though estimates of sheep in the catchment have declined significantly since 2000.

Regulating Services. The main regulating services assessed were climate regulation, water purification, flood mitigation, soil and sediment retention services, and biodiversity (habitat provision).

Climate regulation. Estimated stocks were of approximately 1.5 and approximately 8 million tons Soil Organic Carbon (SOC) for the Dargle and the Figile, respectively. Following the National Inventory Reporting approach using tier 2-derived

Table 2. Summary of peatland flows assessment for the Dargle and the Figile (supporting information in Supplement S1 and datasets used are outlined in Table S1).

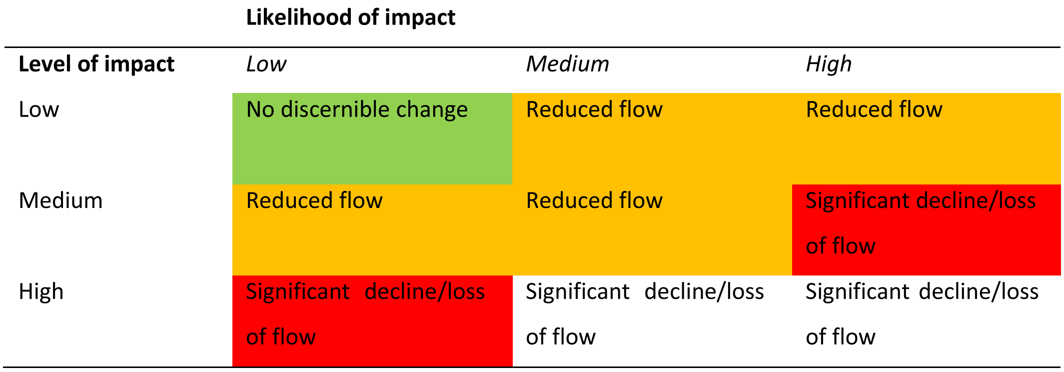
Ecosystem Service	*Description (SEEA EA)*	*Indicator Available*	*Dataset(s) Used (Detailed in Table S1)*	*Dargle*		*Figile*	
				Measure	*Assessment Approach/ Comment*	*Measure*	*Assessment Approach/ Comment*
Provisioning							
Grazing biomass	The ecosystem contributions to the growth of grazed biomass that is an input to the growth of cultivated livestock.	Area of peatland used for grazing sheep/ livestock.	LPIS 2019 (Land Parcel Identification System).	Commonage and permanent pasture on peatland: 2,323 ha; estimated biomass = 1,162 dry matter t/year.	Grazing is a potential cause of ongoing deterioration of condition particularly at headwaters of the catchment.	Not relevant (approximately 8 ha LPIS plots reported for environmental schemes mainly).	Grazing not extensive on peatlands but we note that extensive areas of grasslands were developed on former peatlands in the catchment.
Regulating							
Climate regulation	The ecosystem contributions to the regulation of the chemical composition of the atmosphere and oceans that affect global climate through the accumulation and retention of carbon and other GHG (e.g. methane) in ecosystems and the ability of ecosystems to remove carbon from the atmosphere.	Carbon stock: presence of peatland (extent and type).	CORINE (2018) verified by SIS Peat soil texture and SOC maps (2019).	1,548,751 t SOC	Area CORINE 2018 peatlands on peat soil texture @ 750 t C/ha (bogs) and 277 t C/ha (heathland).	8,067,364 t SOC	Area CORINE 2018 peatlands on peat soil texture @ 850 t C/ha.
		Carbon emissions: drainage and land use.	CORINE (2018) verified by SIS Peat soil texture; NIR methodology.	7,080 t C pa	Area CORINE 2018 peatlands on peat soil texture with EFs based on NIR.	18,887 t C pa	Area CORINE 2018 peatlands on peat soil texture with EFs based on NIR.
Water purification (water quality regulation)	The ecosystem contributions to the restoration and maintenance of the chemical condition of surface water and groundwater bodies through the breakdown or removal of nutrients and other pollutants by ecosystem components that mitigate the harmful effects of the pollutants on human use or health.	Risk assessment of achieving good ecological status at sub basin level.	WFD 2018 (number of sub basins *At Risk* due to peatland degradation).	Not relevant.	Peatland extraction or degradation not highlighted as a pressure.	Nine of 11 sub-basins considered *At Risk* of achieving good ecological status due to peat extraction.	Degraded peatlands can give rise to elevated levels of ammonia in draining waters; siltation and long-term drainage can affect both water quality and hydro-morphology.
River flood mitigation services	The ecosystem contributions of riparian vegetation which provides structure and a physical barrier to high water levels and thus mitigates the impacts of floods on local communities.	Records of flooding in catchment.	OPW flood datasets.	Eighteen recurring and three single flood events.	Data are indicative of potential risk of flooding but modeling at catchment scale is required.	Six recurring and four single flood events.	Data are indicative of potential risk of flooding but modeling at catchment scale is required.

Table 2. Continued

Ecosystem Service	Description (SEEA EA)	Indicator Available	Dataset(s) Used (Detailed in Table S1)	Dargle		Figile	
				Measure	*Assessment Approach/ Comment*	*Measure*	*Assessment Approach/ Comment*
Soil and sediment retention (Landslide mitigation services)	The ecosystem contributions, particularly the stabilizing effects of vegetation, that mitigates or prevents potential damage to human health and safety and damaging effects to buildings and infrastructure that arise from the mass movement (wasting) of soil and rock.	Records of landslides in catchment/ Soil vulnerability maps.	GSI Soil vulnerability datasets.	Landslide events Dargle: 66. Soil vulnerability is *Moderate to High* for peatland areas.	Landslides relating to peat slippage can be triggered by anthropogenic and climatic pressures.	Landslide events in the Figile: 1. Soil vulnerability is *Low* for peatland areas.	One landslide recorded relating to slippage of a canal bank (not related to peatlands).
Nursery population and habitat maintenance services	The ecosystem contributions necessary for sustaining populations of species that economic units ultimately use or enjoy either through the maintenance of habitats (e.g. for nurseries or migration) or the protection of natural gene pools.	Extent and type of peatland habitats and species.	Article 17 data, Raised bog remnant surveys, NPWS MAES 2016 maps.	3,608 ha of Annex I peatland habitats (blanket bog, wet heathland, and fen); High level of policy-relevant species present (*Medium to High*).	Peatland habitats are present, but they are in bad condition; no records of Annex I Birds Directive species present (typical peatland species).	264 ha of Annex I peatland habitats (active raised bog); policy-relevant species present (*Medium to Low*).	Almost complete loss of raised bog habitat and associated peatland species; no records of Annex I Birds Directive species present (typical peatland species).
Cultural							
Recreation/ amenity	The ecosystem contributions, in particular through the biophysical characteristics and qualities of ecosystems, that enable people to use and enjoy the environment through direct, in-situ, physical and experiential interactions with the environment.	Extent of peatlands; access trails and parking points.	Strava data showing use intensity.	Numbers accessing peatlands in the catchment not available but Strava data shows ongoing use.	Upland peatland areas show intensive use for recreation (walking trails exhibit erosion).	Numbers accessing peatlands in the catchment not available but Strava data shows ongoing use.	Limited recreational use except where parking and trails facilitate access around Mountlucas Wind Farm, Lullymore, and Lodge Bog.
Education, scientific, and research services	The ecosystem contributions, in particular through the biophysical characteristics and qualities of ecosystems, that enable people to use the environment through intellectual interactions with the environment.	Education and research centers present.	No datasets: data limited to local site anecdotal knowledge; urban population.	No data.	Upland bog sites are regularly used by all levels of education.	Bog of Allen Nature Centre: 2,300 annual visitors; Lullymore Discovery Park: 54,500 fee-paying 2019.	Two educational centers in the Figile are focused on peatlands.

Table 2. Continued

Ecosystem Service	Description (SEEA EA)	Indicator Available	Dataset(s) Used (Detailed in Table S1)	Dargle		Figile	
				Measure	Assessment Approach/ Comment	Measure	Assessment Approach/ Comment
Non-use services							
Ecosystem and species appreciation	Ecosystem and species appreciation concerns the well-being that people derive from the existence and preservation of the environment for current and future generations, irrespective of any direct or indirect use.	Area designated under Natura 2000 and national designations; protected surface waterbodies (species).	SAC, SPA designations and National designations (NHA, pNHA, nature reserves).	All peatlands designated Natura 2000 sites; one surface waterbody protected for salmonids.	All peatland habitats (approximately 20% of the catchment) included in Natura 2000 sites.	One active raised bog area designated (Daingean Bog, 180 ha).	Less than 1% of the catchment, and <1.5% of the peatland area, designated for peatland habitats and species.
Abiotic flows							
Peat for energy	Flows of energy from nonrenewable sources such as peat are abiotic flows from geological resources.	Domestic use: number of households using peat.	Small area census data.	No. of households using peat: 52 (0.15% total households in catchment).	Historical effects of turf banks evident and ongoing impacts through drainage; no obvious signs of active turf cutting.	No. of households using peat: 1,451 (50.52% total households in catchment).	Extensive turf cutting areas evident at edges of all peatlands in catchment.
		Area of bare peat industrially developed.	Peat company land holding datasets.	Not relevant.	Not relevant.	Estimated industrial peat extraction in 2018 was 744,636 total tons.	Extensive bare peat areas with intact drainage networks and continued disturbance evident; likely to reduce as peat extraction activities reduce and rehabilitation commences.
Wind energy	Energy inputs from renewable sources.	Energy output from wind farms.	Wind energy data.	Not relevant.	Not relevant.	80 MW potential.	Wind energy reliant on intensity and speed of wind.



	Likelihood of impact		
Level of impact	*Low*	*Medium*	*High*
Low	No discernible change	Reduced flow	Reduced flow
Medium	Reduced flow	Reduced flow	Significant decline/loss of flow
High	Significant decline/loss of flow	Significant decline/loss of flow	Significant decline/loss of flow

Figure 4. Risk register scoring matrix following from Mace et al. (2015). The color coding is outlined as follows: green: no/minimal discernible change in flows; amber: reduced flows; red: significant decline in flows.

carbon dioxide emissions for drained peatlands and tier 1 emission factors for dissolved organic carbon lost through fluvial emissions (Wilson et al. 2015; Duffy et al. 2021), highlighted peatlands in both catchments are likely net sources of carbon (7,080 and 18,871 t C emitted in the Dargle and the Figile per annum, respectively). The Figile has the highest carbon stock and similarly the highest estimated emissions.

Water purification and flood mitigation services. In the absence of site-specific data and modeling, using drainage as an indicator of likely service flow (Martin-Ortega et al. 2014, 2021), it is inferred that in their present condition, these services are either not provided by the peatlands in either catchment or are present at a reduced level (depending on drainage intensity and vegetation cover). Supporting Water Framework Directive data available for the Figile showed that due to the peat extraction pressures most of the catchment sub-basins were deemed *At Risk* of achieving good ecological status. Loss of flood mitigation services may be inferred from flooding events in both catchments, particularly in the Dargle, but this requires further analysis.

Landslide mitigation services. Landslide vulnerability datasets highlighted that upland areas in the Dargle are considered highly susceptible to landslides (66 recorded landslide events) while those in the Figile (one recorded landslide event) are considered of low susceptibility.

Habitat maintenance services. All of the peatlands in the Dargle are Annex I habitats, conserved within EU Natura 2000 sites. Less than 1% of the peatlands in the Figile are designated. Indicator maps developed as part of the national MAES project (Parker et al. 2016) showed relatively higher occurrence of nature conservation policy-relevant species in the Dargle than the Figile.

Cultural Services. *Recreation.* While data are not gathered at catchment level, using indicators of recreational use intensity (Strava datasets) showed that limited areas of peatlands are used for recreation in both catchments. This comprised walking in the upland peatlands of the Dargle and walking/running along trackways developed through industrial cutaway peatlands in the Figile (mainly on off-road maintenance access networks through a wind farm site).

Education. The Dargle is proximal to a number of education institutes in the adjoining urban population centers. The Figile is the location of two peatland education centers targeted at primary and secondary levels (Irish Peatland Conservation Council and Lullymore Heritage Discovery Park). In 2019 approximately 55,000 visitors were recorded, with higher levels visiting Lullymore Heritage Discovery Park which has a combined historical and peatland education offering.

Flows Relating to Non-use Values. *Ecosystem appreciation.* The main indicator of this flow is the area of peatlands designated, highest in the Dargle (all peatlands designated, approximately 20% catchment area) and significantly lower (approximately 1% peatlands) in the Figile.

Abiotic Flows. *Peat for energy.* Peat use in domestic households is low in the Dargle (<1% of households) with a higher level of use in the Figile (over 50% of the total households using peat for domestic purposes). Potential industrial peat extraction volumes (based on area of bare peat in 2018), were estimated at 750,000 t of dry peat, with 648,745 t reported as combusted in 2018 in the 124 MW peat and biomass fired electricity generating station in the catchment.

Wind energy. One wind farm is operational in the Figile, developed on an industrial cutaway peatland (Mountlucas wind farm) with an installed generating capacity of 80 MW; a second wind farm is in construction with planned generating capacity of 75 MW.

Benefits and Beneficiaries

The main benefits and beneficiaries of ecosystem services are highlighted in Table 3. Production of food and fiber (sheep production) and energy from peat (an abiotic flow) were the main benefits of focus in the Dargle and the Figile, respectively. Other benefits relate to climate, water, and biodiversity as well as health and well-being. Emerging benefits in recent decades relate to recreational and educational use, as well as energy generation from wind (Figile only).

Informing Restoration Needs Through a Risk Register of Peatland Flows

Based on the assessment of stocks as being in bad condition (Farrell et al. 2021*c*), and an assessment of ecosystem services, we allocated a RAG scoring to peatland flows in each catchment (Table 3). We also outlined potential restorative actions to reduce the impacts on and reduce negative and declining trends in flow, highlighting synergies between the SEEA EA and the SER Standards in Table 4. The detailed relationships between stocks, flows, and pressures and threats in each catchment are outlined in Table S2.

Overall, for both study catchments, because of the underlying condition and effects of either historical and/or ongoing pressures, flows relating to regulatory services in particular show risk of reductions or significant declines/losses with some differences relating to the peatland type and geographical context.

Dargle Flows. In the Dargle, overgrazing by sheep and drainage and cutting for fuel are two of the main pressures that have reduced in intensity; however, the peatlands still show effects

Table 3. Risk register for study catchments: ecosystem services are linked to likely benefits and beneficiaries in each catchment. A RAG scoring is allocated to each service/benefit with proposed restorative actions required (green: no/minimal discernible change in flows; amber: reduced flows; red: significant decline in flows).

Service/Flows	*Benefit*	*Likely Beneficiaries*	*Dargle*	*Figile*
Provisioning services				
Grazing biomass	Food/fiber production	Primary producer (farmer/ landowner)	🟧 Reduce/Eliminate grazing.	🟩 Monitor.
Regulating services				
Climate regulation	Equitable climate	Global society	🟥 Assess eco-hydrology and implement drain blocking plan.	🟥 Assess eco-hydrology and implement drain blocking plan.
Water purification	Good ecological status waterbodies	Government Departments	🟥 Eliminate grazing and reduce erosion (revegetation measures).	🟥 Regulate domestic cutover areas and ensure rehabilitation across all peat extraction areas.
River flood mitigation	Flood events reduced; damage avoided to livelihoods, human health, and ecosystems	Local authority/ Floods authority (OPW)	🟥 Assess hydrology and implement drain blocking plan.	🟥 Assess hydrology and implement drain blocking plan.
Landslide mitigation	Damage to livelihoods, human health, and ecosystems avoided	Householders	🟧 Linked to other restorative activities relating to habitat and hydrology.	🟩 Monitor.
Habitat maintenance	Viable populations/areas for species and habitats	Global society	🟥 Restore hydrology and revegetate bare peat; grazing management.	🟧 Implement restoration and rehabilitation measures across catchment.
Cultural services				
Recreation/ amenity	Human health and well-being	General public (local and visitors)	🟧 Reduce access in and revegetate/ restore degraded areas; establish boardwalks.	🟩 Engage communities in restoration and rehabilitation.
Education	Human health and well-being	Education provider	🟩 Engage scientific community to develop restoration plans.	🟩 Engage scientific community to develop restoration plans.
Non-use services				
Ecosystem appreciation	Non-use/existence benefits	Global society	🟥 Develop public awareness; Restore hydrology and revegetate bare peat; grazing management.	🟧 Develop public awareness about peatlands; engage communities in restoration and rehabilitation.
Abiotic flows				
Peat energy	Electricity generation	Peat extraction company	Not relevant.	Trend: reducing.
	Domestic fuel	Householders	Trend: evidence of historical cutting but not active.	Trend: no change.
Wind energy	Electricity generation	Wind energy company	Not relevant.	Trend: increasing.

of these pressures in terms of drainage and exposure of bare peat. Uncontrolled burning and an increase in recreational use are ongoing pressures. The combined effects of past and present pressures have led to a reduction in available grazing, with significant declines in and reversal of flows relating to climate, water, and biodiversity, and negative effects on soil stability and ecosystem appreciation. While the Dargle upland peatlands are used for recreation, exposure of bare peat and erosion may lead to these areas being less appealing for recreational use where degradation increases, and/or access may be required to be restricted to allow for peatland restoration measures. Education is likely to remain a benefit despite condition of the peatlands.

Dargle Restoration. Upland peatlands are slow to recover from degradation, requiring active measures to stabilize bare peat and restore eco-hydrological characteristics of active (peat-forming) peatlands which underpin delivery of peatland ecosystem services and benefits. Restorative measures required include elimination/reduction of grazing to allow full recovery of vegetation, targeted drain blocking, and in recreational areas, installation of boardwalks to restrict and reduce trampling (Thom et al. 2019). Given that all the peatlands in the Dargle are listed in Annex I habitats, restoration of active blanket bog/wet heath mosaics is a legal requirement under the EU Habitats Directive. However, localized areas, having crossed a threshold in terms of restoration, will require restorative measures to revegetate exposed subsoils and stabilize bare eroding peat to reduce and reverse losses of carbon and sediment.

Figile Flows. In the Figile, peat extraction (an abiotic flow) is an ongoing pressure with significant declines in and reversal of flows relating to climate, water, and biodiversity. Because of the low-intensity use of peatlands for grazing, and the low elevation and gradients there were no discernible effects on benefits relating to food/fiber productions and/or landslides. Similarly, for education and recreation related flows, these activities have been carried out at a low intensity historically across the peatlands but are likely to increase as the rehabilitation of large-scale industrial cutaway peatlands progresses. There were no data for domestic cutting areas though the activity is widespread in the catchment.

Figile Restoration. Apart from fragments of Annex I habitats (where restoration of raised bog is legally required under the EU Habitats Directive), most of the peatlands in the Figile have crossed a threshold in terms of their potential to be restored to the historical reference (raised bog) and are likely to revert to fen and wet woodland mosaics (Rowlands & Feehan 2000). Rehabilitation of the industrial cutaway peatland will require restorative activities (drain blocking and revegetation) to stabilize the peatlands and reduce negative flows relating to climate, water, and biodiversity (Andersen et al. 2018). The time frame for reductions and potential reversal of negative flows will vary across the peatland areas depending on peat depth and type, hydrological recovery, and the rate of recovery of ecosystem processes.

Table 4. Aligning the SER standards and the UN SEEA EA accounting framework.

SER Principle	*Activity Involved*	*Relationship to UN SEEA EA*
P1 and P2: Engages stakeholders and draws on many types of knowledge	Stakeholder engagement (local and national).	An integral aspect of SEEA EA.
P3: Is informed by native reference ecosystems, while considering environmental change	Set historical reference and determine present type.	Informed by SEEA EA extent and condition accounts.
	Establish future reference types (link with reference condition based on knowledge of past and present condition.	Based on SEEA EA accounts which track changes over time and should indicate threshold for restoration/recovery.
P4: Supports ecosystem recovery processes	Restoration measures proposed (from the SER family of restorative measures).	
P5: Is assessed against clear goals and objectives, using measurable indicators	Goals and objectives set with measurable indicators.	Tracked by SEEA EA extent, condition, and flow accounts.
P6: Seeks the highest level of ecosystem recovery possible	Established targets informed by reference condition, based on knowledge of present condition and thresholds for restoration.	Informed by SEEA EA accounts.
P7: Gains cumulative value when applied at large scales	A standardized approach to track changes over a range of sites and regions.	Provided by the SEEA EA framework.
P8: Is part of a continuum of restorative activities	Note: from the SER Standards all restoration plans to enhance positive human connections with nature.	This re-enforces the role of iterative engagement outlined by both SER and SEEA EA frameworks.

Discussion

Peatlands: Natural Capital Poised for Restoration

Peatland ecosystems are globally important natural capital (Bonn et al. 2016), and degraded peatlands are at risk of not delivering and sustaining ecosystem flows (services and benefits). Our findings reflect that of Mace et al. (2015) where mountain, moors, and heathland habitats were assessed to be at high risk of losing their ability to sustain flows relating to clean water, habitat, and climate regulation. Peatland restoration can reduce these risks, but in order to develop strategic restoration plans and allocate resources, clear targets must be set in relation to what peatlands are to be restored, where, and why. Given the scale of peatland degradation globally, and the range of starting conditions, targeting investment is essential both to reduce the likelihood of negative impacts arising from degraded peatlands (e.g. increased carbon emissions, risk of fire, and/or peat slides), and to maximize returns for recognized policy-relevant benefits, particularly in relation to responding to climate and biodiversity targets, and sustainable livelihoods (Bonn et al. 2016).

These issues can be addressed based on an understanding of peatland stocks (extent and condition), given that different levels of investment will be required depending on the degree of degradation and will yield varying levels of return either through improved condition of stocks or changes in flow (Mace et al. 2015). Trade-offs must be guided by legal obligations in relation to restoration of stocks such as those set out for peatland habitats under the EU Habitats Directive, as well as national targets relating to flows relating to climate, water, and human well-being, as outlined, e.g. under National Recovery and Resilience Plans developed in 2021 (DEPR 2021).

As shown in this study, despite limited data, use of a risk register to identify opportunities to restore peatland ecosystem flows, can help identify restoration targets, particularly those relating to land-use change to deliver carbon emission reductions set under EU and global targets and legal requirements relating to EU Water Framework Directive obligations (Farrell et al. 2021*b*, 2021*c*). Combining the risk register approach with information gathered under the SEEA EA framework thereby serves to identify ecosystem stocks requiring restoration (Farrell et al. 2021*c*) and highlight opportunities to invest in reducing risks relating to, and restoration of, flows, including for peatlands that have crossed the threshold of restoration and cannot be restored to their former type and/or condition. In these instances, restoration measures to conserve carbon stores and reduce carbon emissions from degraded peatlands have significant potential to deliver high returns (in terms of carbon) on investment (Joosten et al. 2016).

The intensities of use of provisioning services (grazing) and abiotic flows (peat energy) across peatlands globally have changed over time as reflected in our study catchments. These changes reflect a switch from previously sustainable flows (low level grazing) and low-level pressures (hand-cut turf extraction), to present unsustainable flows (overgrazing) and high-level pressures (mechanized, industrial scale peat extraction). Other pressures highlighted by Farrell et al. (2021*b*, 2021*c*) were the conversion of peatlands to other ecosystem types such as grasslands and commercial forests (by up to 50%), while increased focus on cultural services (such as recreation in the Dargle) and a shift in focus to renewable energy (such as in the Figile) are relatively new land uses and potential pressures. These will require trade-offs in terms of future peatland flows (for example drain blocking of degraded peatlands versus drainage for infrastructure) as shown across Ireland and the United Kingdom (Renou-Wilson & Farrell 2009; Smith et al. 2014). The changes in benefits and beneficiaries reflect European and national policies relating to agriculture, forestry, and energy, and more recently climate change, highlighting the integrated effects of land-use policy on ecosystem stocks and flows, reflected in the EU Green Deal policy framework (Vysna et al. 2021).

Aligning an array of available datasets under the SEEA EA framework supported development of rudimentary peatland ecosystem accounts for this study. Additional data relating to peat depth and type (essential to assess carbon stocks, beyond 1 m depth where relevant, and carbon flows more accurately), drainage intensity (an indicator both of peatland use and condition), and biodiversity (indicator bird species of peatlands as used in U.K. peatland ecosystem accounts) would support the extension of this work. We note that there are limited data available relating to the contribution of peatlands for water provision in Ireland (Flynn et al. 2021), although this is highlighted as a priority service in the U.K. peatland accounts (ONS 2019). Similarly, there are limited data on regulation of water flows. Both of these aspects require detailed hydrological modeling and analysis. From the cultural services perspective, despite public perceptions changing to reflect a deeper appreciation of the full range of ecosystem services that peatlands provide (Flood et al. 2021), data to quantify the broader suite of cultural services (outside of recreational use) are lacking. In relation to abiotic flows, while data were available for regulated industrial sites there were no data relating to unregulated industrial and/or domestic cut sites which are extensive in Ireland (Connolly 2019; Farrell et al. 2021*c*). Mapping and assessment of the scale of this activity are required both to design and implement regulatory mechanisms, and develop restorative guidance, to inform potential measures to reduce associated negative flows particularly those related to climate and water.

Combining Tools for Restoration to Build Capacity across Sectors

Building technical capacity across disciplines is recognized as essential to implement and achieve targets under the UN Decade on Ecosystem Restoration (UN 2020; Farrell et al. 2021*a*), as well as to facilitate integration of regional policy targets set under the EU Biodiversity Strategy for 2030, the EU Habitats and the EU Water Framework Directives (Farrell et al. 2021*b*, 2021*c*). Sharing common drivers, such as the need to navigate trade-offs associated with land management priorities (Gann et al. 2019; UNSD 2021), there is considerable scope for synergy between the frameworks of the SEEA EA and SER Standards to develop integrated, cross sectoral approaches.

Under the SER Standards, ecological restoration is outlined as one of several approaches that address damage to ecosystems, with Principle 8 outlining the allied approaches or family of restorative activities that can be conceived of as a "Restorative Continuum" (Gann et al. 2019). Restorative measures range from reducing societal impacts (such as aligning policy measures to reduce pressures) to taking active physical interventions (Gann et al. 2019). Common steps to guide the restorative pathway/continuum in the study catchments, which link with the core SEEA EA accounting framework, can be transferred to any peatland area, and these include:

- Understanding the past, present, and future extent, type, and reference condition levels of peatland stocks: this requires an assessment of peatland characteristics including peat type and depth, vegetation, and eco-hydrology.
- Understanding trends in flows of services and likely benefits and beneficiaries, incorporating an assessment of pressures and threats.
- Identification of short- and long-term restorative measures such as changes in management and/or hydrological repair and revegetation, to effect restoration of stocks and/or flows.
- Stakeholder engagement from local to national policy level. Identified as Principle 1 of the SER Standards (Gann et al. 2019), this aspect is integral to the SEEA EA approach (Farrell et al. 2021*a*).

Once realistic peatland restoration targets are established, planning and implementation of restoration activities using frameworks such as the SER Standards, as well as the monitoring of changes over time, are essential. Tracking changes over time (either from a stock or flow perspective) using the SEEA EA framework can support a risk register approach as demonstrated here and/or provide a readymade monitoring dashboard to ensure targets are realized, supporting adjustments over time, but also serving to track changes and therefore avoid unintentional losses across other ecosystem types (UNSD 2021).

Next Steps to Align Policy and Peatland Restoration

Despite limited data, applying the SEEA EA alongside expert knowledge of peatland ecology highlighted an effective means to develop a risk register to identify opportunities for peatland restoration. Along with their role in climate regulation, restoring peatland ecosystem processes can deliver benefits across an array of policy areas including agriculture, water, nature, and health and well-being. While a number of plans and strategies, including the EU restoration plan highlight the need for cross-sectoral collaboration (Maes et al. 2020; Vysna et al. 2021), efforts to date to deliver on peatland restoration across Europe have been relatively small scale (Anderson et al. 2018). Building on progress to develop payments for ecosystem services schemes for landowners (Reed et al. 2014), a well-informed and resourced global/European peatland restoration strategy aligned with ecosystem accounting frameworks such as the SEEA EA, would support better decisions for optimal returns across an integrated range of flows relating to climate, water, biodiversity, and sustainable development (Maes et al. 2020). Future research in economic and social assessments of peatland restoration, building on existing economic impact assessment approaches (Glenk et al. 2014) as well as extending this approach to other ecosystem types, at a range of scales, would further illustrate explicit links between peatlands and society. For each ecosystem type, the ecological nonlinearities and thresholds of each ecosystem type must be recognized (Mace et al. 2015) requiring ongoing collaborative and interdisciplinary work by ecologists, social scientists, and economists (Farrell et al. 2021*a*).

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LITERATURE CITED

Andersen R, Farrell C, Graf M, Muller F, Calvar E, Frankard P, Caporn S, Anderson P (2018) An overview of the progress and challenges of peatland restoration in Western Europe. Restoration Ecology 25:271–282. https://doi.org/10.1111/rec.12415

Bateman I, Mace G (2020) The natural capital framework for sustainably efficient and equitable decision making. Nature Sustainability 3:776–783. https://doi.org/10.1038/s41893-020-0552-3

Bonn A, Allott T, Evans M, Joosten H, Stoneman R (2016) Peatland restoration and ecosystem services: an introduction. Pages 1–16. In: Bonn A, Allot T, Evans M, Joosten J, Stoneman R (eds) Peatland restoration and ecosystem services: science, policy and practice. Cambridge, UK: Cambridge University Press

Connolly J, Holden NM (2009) Mapping peat soils in Ireland: updating the derived Irish peat map. Irish Geography 42:343–352. https://doi.org/10.1080/00750770903407989

Connolly J (2019) Mapping land use on Irish peatlands using medium resolution satellite imagery. Irish Geography 51:187–204. https://doi.org/10.2014/igj.v51i2.1371

Dasgupta P (2021) The economics of biodiversity: the Dasgupta review. HM Treasury, London, United Kingdom. https://www.gov.uk/government/publications/final-report-the-economics-of-biodiversity-the-dasgupta-review (accessed 31 Oct 2021)

DEPR (Department of Public Expenditure and Reform) (2021) Ireland's national recovery and resilience plan 2021. Government Publications Office. https://www.gov.ie/en/publication/d4939-national-recovery-and-resilience-plan-2021/ (accessed 3 Nov 2021)

Díaz S, Settele J, Brondízio ES, Ngo HT, Agard J, Arneth A, et al. (2019) Pervasive human-driven decline of life on Earth points to the need for transformative change. Science 366:eaax3100. https://doi.org/10.1126/science.aax3100

Duffy P, Black K, Fahey D, Hyde B, Kehoe A, Murphy J, Quirke B, Ryan AM, Ponzi J (2021) Greenhouse gas emissions 1990–2019 reported to the United Nations framework convention on climate change. Environmental Protection Agency, Ireland. https://www.epa.ie/publications/monitoring--assessment/climate-change/air-emissions/Ireland_NIR-2021_cover.pdf (accessed 1 Nov 2021)

Eigenraam ME, Obst C (2018) Extending the production boundary of the System of National Accounts (SNA) to classify and account for ecosystem services. Ecosystem Health and Sustainability 4:247–260. https://doi.org/10.1080/20964129.2018.1524718

Evans C, Bonn A, Holden J, Reed M, Evans M, 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. https://doi.org/10.1016/j.ecoser.2014.06.013

Farrell C, Aronson J, Daily G, Hein L, Obst C, Woodworth P, Stout J (2021a) Natural capital approaches: shifting the UN decade on ecosystem restoration from aspiration to reality. Restoration Ecology. https://doi.org/10.1111/rec.13613

Farrell C, Coleman L, Kelly-Quinn M, Obst C, Eigenraam M, Norton D, O'Donoghue C, Kinsella S, Delargy O, Stout J (2021b) Applying the system of environmental economic accounting-ecosystem accounting (SEEA EA) framework at catchment scale to develop ecosystem extent and condition accounts. One Ecosystem 6:e65582. https://doi.org/10.3897/oneeco.6.e65582

Farrell C, Coleman L, Kelly-Quinn M, Obst C, Eigenraam M, Norton D, et al. (2021c) Developing peatland ecosystem accounts to guide targets for restoration. One Ecosystem 6:e76838. https://doi.org/10.3897/oneeco.6.e76838

Flood K, Mahon M, McDonagh J (2021) Assigning value to cultural ecosystem services: the significance of memory and imagination in the conservation of Irish peatlands. Ecosystem Services 50:e101326. https://doi.org/10.1016/j.ecoser.2021.101326

Flynn R, Mackin F, Renou-Wilson F (2021) Towards the quantification of blanket bog ecosystem services to water (2015-NC-MS-5) EPA Research Report. Environmental Protection Agency, Ireland. https://www.epa.ie/publications/research/water/Research_Report_378.pdf (accessed 1 Nov 2021)

Fossitt JA (2000) A guide to habitats in Ireland. The Heritage Council, Kilkenny, Ireland. https://www.npws.ie/sites/default/files/publications/pdf/A%20Guide%20to%20Habitats%20in%20Ireland%20-%20Fossitt.pdf

Gann GD, McDonald T, Walder B, Aronson J, Nelson C, Jonson J, et al. (2019) International principles and standards for the practice of ecological restoration. 2nd edition. Restoration Ecology 27:S3–S46. https://doi.org/10.1111/rec.13035

Glenk K, Schaafsma M, Moxey A, Martin-Ortega J, Hanley N (2014) A framework for valuing spatially targeted peatland restoration. Ecosystem Services 9:20–33. https://doi.org/10.1016/j.ecoser.2014.02.008

Hein L, Bagstad KJ, Obst C, Edens B, Schenau S, Castillo G, et al. (2020a) Progress in natural capital accounting for ecosystems. Science 367:514–515. https://doi.org/10.1126/science.aaz8901

Hein L, Remme R, Schenau S, Bogaart P, Lof M, Horlings E (2020b) Ecosystem accounting in the Netherlands. Ecosystem Services 44:101118. https://doi.org/10.1016/j.ecoser.2020.101118

IPCC (2021) Climate change 2021: the physical science basis. Contribution of Working Group I to the sixth assessment report of the Intergovernmental Panel on Climate Change. Cambridge, UK: Cambridge University Press. https://www.ipcc.ch/report/ar6/wg1/#FullReport (accessed 4 Nov 2021)

Joosten H, Sirin A, Couwenberg J, Laine J, Smith P (2016) The role of peatlands in climate change. In: Bonn A, Allot T, Evans M, Joosten J, Stoneman R (eds) Peatland restoration and ecosystem services: science, policy and practice. Cambridge, UK: Cambridge University Press

Keith DA, Ferrer-Paris JR, Nicholson E, Kingsford R (2020) The IUCN global ecosystem typology 2.0 descriptive profiles for biomes and ecosystem functional groups. Switzerland: IUCN. https://doi.org/10.2305/IUCN.CH.2020.13.en

Köhl M, Lasco R, Cifuentes M, Jonsson Ö, Korhonen K, Mundhenk P, de Jesus Navar J, Stinson G (2015) Changes in forest production, biomass and carbon: results from the 2015 UN FAO global Forest resource assessment. Forest Ecology and Management 352:21–34. https://doi.org/10.1016/j.foreco.2015.05.036

Mace GM, Hails RS, Cryle P, Harlow J, Clarke SJ (2015) Towards a risk register for natural capital. Journal of Applied Ecology 52:641–653. https://doi.org/10.1111/1365-2664.12431

Obst CG (2015) Reflections on natural capital accounting at the national level: advances in the system of environmental-economic accounting. Sustainability Accounting, Management and Policy Journal 6:315–339. https://doi.org/10.1108/SAMPJ-04-2014-0020

Maes J, Teller A, Erhard M, Condé S, Vallecillo S, Barredo JI, et al. (2020) Mapping and assessment of ecosystems and their services: an EU ecosystem assessment. Luxembourg: Publications Office of the European Union, Ispra. https://doi.org/10.2760/757183

Martin-Ortega J, Allott TH, Glenk K, Schaafsma M (2014) Valuing water quality improvements from peatland restoration: evidence and challenges. Ecosystem Services 9:34–43. https://doi.org/10.1016/j.ecoser.2014.06.007

Martin-Ortega J, Young D, Glenk K, Baird A, Jones L, Rowe E, Evans C, Dallimer M, Reed M (2021) Linking ecosystem changes to their social outcomes: lost in translation. Ecosystem Services 50:101327. https://doi.org/10.1016/j.ecoser.2021.101327

NPWS (2019) The status of EU protected habitats and species in Ireland. Volume 1: summary overview. Ireland: NPWS. https://www.npws.ie/sites/default/files/publications/pdf/NPWS_2019_Vol1_Summary_Article17.pdf (accessed 1 Nov 2021)

Obst C, Hein L, Edens B (2016) National accounting and the valuation of ecosystem assets and their services. Environmental and Resource Economics 64:1–23. https://doi.org/10.1007/s10640-015-9921-1

Office of National Statistics (2019) UK natural capital: peatlands. Statistical Bulletin, UK. https://www.ons.gov.uk/economy/environmentalaccounts/bulletins/uknaturalcapitalforpeatlands/naturalcapitalaccounts (accessed 4 Nov 2021)

Parker N, Naumann E-K, 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, No. 95. National Parks and Wildlife Service, Department of Arts, Heritage, Regional, Rural and Gaeltacht Affairs, Ireland. https://www.npws.ie/sites/default/files/publications/pdf/IWM95_appendices.pdf (accessed 3 Nov 2021)

Reed MS, Moxey A, Prager K, Hanley N, Skates J, Evans C, Glenk K, Thompson K (2014) Payment by potential results: paying for ecosystem services in Agri-environment schemes in UK peatlands. Ecosystem Services 9:44–53. https://doi.org/10.1016/j.ecoser.2014.06.008

Renou-Wilson F, Farrell CA (2009) Peatland vulnerability to energy-related climate change policy in Ireland: the case of wind farms. Mires and Peat 4: 1–11. http://www.mires-and-peat.net/pages/volumes/map04/map0408.php (accessed 6 Jan 2022).

Renou-Wilson F, Moser G, Fallon D, Farrell CA, Müller C, Wilson D (2019) Rewetting degraded peatlands for climate and biodiversity benefits: results from two raised bogs. Ecological Engineering 127:547–560. https://doi.org/10.1016/j.ecoleng.2018.02.014

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 Research Report 250, Ireland. https://www.epa.ie/publications/research/climate-change/Research_Report_250.pdf (accessed 1 Nov 2021)

Rowlands R, Feehan J (2000) The ecological future of industrially milled cutaway peatlands in Ireland. Aspects of Applied Biology 58:263–269

Smith J, Nayak DR, Smith P (2014) Wind farms on undegraded peatlands are unlikely to reduce future carbon emissions. Energy Policy 66:585–591. https://doi.org/10.1016/j.enpol.2013.10.066

Steffen W, Richardson K, Rockström J, Cornell SE, Fetzer I, Bennett EM, et al. (2015) Planetary boundaries: guiding human development on a changing planet. Science 347:1259855. https://doi.org/10.1126/science.1259855

Thom T, Hanlon A, Lindsay R, Richards J, Stoneman R, Brooks S (2019) Conserving bogs: the management handbook. IUCN UK Peatland Programme. https://www.iucn-uk-peatlandprogramme.org/resources/restoration-practice/conservation-handbook (accessed 1 Nov 2021)

UN (2019) Resolution adopted by the General Assembly on 1 March 2019. https://undocs.org/A/RES/73/284 (accessed 31 Oct 2021)

UN (2020) The United Nations decade on ecosystem restoration: strategy. UN. https://wedocs.unep.org/bitstream/handle/20.500.11822/31813/ERDStrat.pdf?sequence=1&isAllowed=y (accessed 3 Nov 2011)

UNSD (2021) System of environmental-economic accounting—ecosystem accounting final draft. New York, NY: Department of Economic and Social

Affairs, Statistics Division, United Nations. https://unstats.un.org/unsd/statcom/52nd-session/documents/BG-3f-SEEA-EA_Final_draft-E.pdf (accessed 1 Nov 2021)

Urák I, Hartel T, Gallé R, Balog A (2017) Worldwide peatland degradations and the related carbon dioxide emissions: the importance of policy regulations. Environmental Science & Policy 69:57–64. https://doi.org/10.1016/j.envsci.2016.12.012

van der Velde Y, Temme A, Nijp J, Braakhekke M, van Voorn G, Dekker S, et al. (2021) Emerging forest–peatland bistability and resilience of European peatland carbon stores. Proceedings of the National Academy of Sciences of the United States of America 118:e2101742118. https://doi.org/10.1073/pnas.2101742118

Vysna V, Maes J, Petersen JE, La Notte A, Vallecillo S, Aizpurua N, Ivits E, Teller A (2021) Accounting for ecosystems and their services in the European Union (INCA). Final report from phase II of the INCA project aiming to develop a pilot for an integrated system of ecosystem accounts for the EU. Statistical report. Publications office of the European Union, Luxembourg. https://ec.europa.eu/eurostat/documents/7870049/12943935/KS-FT-20-002-EN-N.pdf/de44610d-79e5-010a-5675-14fc4d8527d9?t=1624528835061 (accessed 31 Oct 2021)

Wilson D, Dixon SD, Artz RRE, Smith TEL, Evans CD, Owen HJF, 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. https://doi.org/10.5194/bg-12-5291-2015

Supporting Information

The following information may be found in the online version of this article:

Table S1. Datasets used in the study and their relevance.

Table S2. Risk register of flows of service and benefits in (i) the Dargle and (ii) the Figile.

Supplement S1. Services.

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