A review of greenhouse gas emissions and removals from Irish peatlands

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SUMMARY

Since peatlands cover around 20 % of the land area in the Republic of Ireland, their management is of particular significance in reducing national greenhouse gases (GHG) emissions. We reviewed peatland carbon (C) flux studies within Ireland, extracting data for carbon dioxide, methane, and nitrous oxide fluxes, as well as fluvial losses and here propose preliminary country-specific emission factors (EFs) for various peatland land uses and management practices. Using our derived EFs and latest areal estimates, national emissions from peatlands (excluding horticulture and combustion) amount to 1.9 Mt C y^{-1} (± 0.4–3.4 Mt C y^{-1}), with more than half of all peatland GHG emissions coming from grasslands on organic soils and over one-third from domestic extraction drained peatlands. Our analyses suggest that peatland management through rewetting and restoration has the potential to substantially reduce emissions from drained peatlands, and this article attempts to quantify this reduction. This is critically important given the large areas of degraded peatlands that have been earmarked for rewetting in the next decade.

KEY WORDS: carbon, climate change, emission factors, Ireland, peatlands

INTRODUCTION

Peatlands are soils with a high concentration of organic matter and determining the carbon (C) balance of a peatland is complex, presenting multiple challenges to those interested in assessing C fluxes at both the individual-site and regional scales. Natural peatlands have played a vital role in regulating the global climate over the last ten millennia by acting as long-term C sinks (Frolking & Roulet 2007, Nilsson *et al.* 2008, Koehler *et al.* 2011, Rinne *et al.* 2020). Net C accumulation occurs when the amount of carbon dioxide (CO_2) fixed by the peatland vegetation during photosynthesis is greater than that released during respiration by the plants and the microbial communities, in the form of CO_2 and methane (CH_4), and through fluvial transport via dissolved, particulate, and inorganic forms of carbon (i.e., DOC, POC, DIC) (Nilsson *et al.* 2008, Koehler *et al.* 2011, Swenson *et al.* 2019). Land-atmosphere greenhouse gas (GHG) fluxes in peatlands are mainly affected by water table level (Laine *et al.* 1996), vegetation composition and cover (Cooper *et al.* 2014, Strack *et al.* 2016), and by climatic variables (McVeigh *et al.* 2014, Helfter *et al.* 2015). The relatively high water table of natural peatlands at or close to the surface leads to anoxic conditions and reduced plant decomposition (Page & Baird 2016). In degraded peatlands, however, the dynamics of the C cycle are changed when the water table is lowered, often by drainage, turning them from natural C sinks to long-term sources via oxidation (Leifeld & Menichetti 2018). Typically, natural peatlands are a net CO_2 sink and a CH_4 source (Helfter *et al.* 2015), while degraded peatlands are a CO_2 source with reduced CH_4 emissions (Swenson *et al.* 2019). However, low CH_4 emissions in degraded peatlands are offset by large positive net ecosystem exchange (Renou-Wilson *et al.* 2019). Nitrous oxide (N_2O) emissions become significant in nutrient-rich peatlands converted to agriculture or forestry (Leifeld 2018, Liu *et al.* 2020).

Ireland has approximately 1.46 Mha of peatlands, which equates to around 20 % of the total land surface (Tanneberger *et al*. 2017). The two dominant types of peatlands are blanket bogs and raised bogs, which originally covered 774,000 ha and 308,742 ha, respectively (Hammond 1981). Currently, about 85 % of all peatlands are degraded through human activities via conversion to agriculture (mostly grassland) and forestry, and extraction for energy and horticulture (Renou-Wilson 2018). The current area of ‘active bog’ (supporting peat formation and therefore C sequestration) is estimated to be only 1,659 ha for raised bogs and remains unknown for blanket bogs (Renou-Wilson *et al.* 2011, NPWS 2019).

Ireland is obligated to report anthropogenic emissions/removals from peatlands in annual National Inventory Reports (NIR) under the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol requirements (Duffy *et al*. 2021). The second Kyoto Protocol period (2013–2020) has now ended, and the first period of the EU Land Use, Land Use Change and Forestry (LULUCF) regulations under the EU Climate and Energy Framework (European Parliament 2018) will run from 2021–2025 (second period: 2026–2030). Ireland has chosen to elect managed wetlands for the first commitment period under these regulations prior to mandatory accounting for the second period (Renou-Wilson *et al.* 2022).

Ireland's National GHG inventory complies with the methodology described in the Intergovernmental Panel on Climate Change (IPCC) Guidelines (IPCC 2006). The guidelines have been updated with the Wetlands Supplement (IPCC 2014) and read in conjunction with the 2019 Refinement report (IPCC 2019). The Wetlands Supplement combined the best available published data (up to 2013) with emissions/removals stratified by climate region (boreal, temperate and tropical), nutrient status (poor and rich) and drainage (drained and rewetted). For drained peatlands, the emissions/removals were divided between land use categories (LUCs), while rewetted peatlands were assumed to have been converted to one land use (i.e., rewetted).

The IPCC methodology provides three levels (Tiers) of emission factors (EFs) reporting. Tier 1 (default) represents globally applicable EFs; Tier 2 is based on country-specific based empirical data; and Tier 3 uses more complex and dynamic mechanistic models. However, default Tier 1 EFs are limited by data availability and the level to which they could be disaggregated. Moreover, these EFs are based on field data from sites with an imbalanced geographical distribution, weighted towards areas that are climatically and ecologically dissimilar to Ireland. The key limitations from an Irish perspective include the absence of a distinction between industrial (mainly associated with industrial extraction by the semi-state body Bord na Móna in the midlands) and domestic peat extraction as peatland management types. Ireland is unique in possessing a considerable area of peatlands used for 'small-scale' (domestic) peat extraction. This extraction has mainly occurred (and is occurring) on the peatland margins, and in contrast to industrial peat extraction sites, results in the retention of typical, but drier peatland vegetation in the "high bog" (or "uncut bog") (Smith & Crowley, 2020). The majority of peatlands reclaimed for agriculture have been used for grassland where both intensive and extensive grazing is combined with a range of drainage status (Renou-Wilson *et al.* 2014). It is thus necessary to develop a suitable land use category classification to reflect the range of management and land use types for Ireland in the calculation of country-specific EFs.

Currently, Ireland reports emissions from peatlands at the Tier 1 level. The exceptions are the industrial peat extraction sites (Wilson *et al.* 2015) and forests on drained peatlands where country-specific values have been accepted (Duffy *et al.* 2021). In this paper, we reviewed GHG and fluvial C flux studies on Irish peatlands up to 2022. We applied here the methods and scientific approach described in the Wetlands Supplement in an attempt to derive country-specific EFs for GHG fluxes associated with peatlands under LUCs across Ireland. We developed further disaggregation under rewetted and drained conditions and examine the robustness of these new EFs, by comparing them with Tier 1 values and other relatable country-specific Tier 2 EFs. Finally, we assessed existing knowledge gaps and highlighted areas that require future research.

METHODS

Assessing potential refinements

Carbon emissions/removals from peatlands have been stratified only by climate region and nutrient status in the 2006 IPCC Guidelines. The Wetlands Supplement further disaggregated emissions/removals from peatlands by drainage status. However, the Wetlands Supplement considered all rewetted peatlands as one single LUC. Due to data limitations, the current Tier 1 EFs for rewetted peatlands thus include both natural (74 entries) and rewetted (49 entries) peatlands (IPCC 2014, Wilson *et al.* 2016a). In this paper, we report EFs for rewetted peatlands separately. Natural peatlands were used as relative targets for rewetted peatlands, as they have not been affected by human activity (i.e. are unmanaged). However, in terms of Irish peatlands, "near-natural" is a more accurate description of unmanaged peatlands as all Irish peatlands have experienced anthropogenic pressure to some extent.

The Wetlands Supplement provided a minimum standard for developing the classification of land uses on peatlands and gave recommendations to develop, where possible, EFs for regional climate conditions and specific land use activity (IPCC 2014). This paper adopted these recommendations by providing further details, namely: (1) drainage status (shallow and deep drained), (2) previous land use for rewetted peatlands, (3) time since rewetting, (4) management system and intensity, (5) detailed nutrient status (e.g. nitrogen, phosphorus or pH).

Derivation of EFs

We developed a detailed database of annual GHG fluxes and fluvial losses for rewetted and drained Irish peatlands. All studies included in the database used either the closed chamber or eddy covariance (EC) technique to measure GHG fluxes. The chamber method allows measurements of gas fluxes at high spatial resolution and is typically used at sites with low or absent vegetation. The EC towers are widely employed in conditions where vegetation cover is homogeneous and sites are flat, which includes both open and forested peatlands (Alm *et al.* 2007). The soil C balance for drained peatlands under forestry combines soil respiration, the aboveground tree litterfall and the belowground fine-root litter (Jovani-Sancho *et al.* 2021). Living biomass and litter sinks were added only for the calculation of the total C emissions/removals. In the case of grassland, the biomass (grass) exports were included for the grassland EFs.

Annual CO_2-C, CH_4-C, N_2O-N fluxes and fluvial C losses were extracted from published literature (as per IPCC methodology) and allocated to the relevant, new or existing LUC. Peatland sites typically consist of several sub-sites (or ecotopes), which are identified with similar environmental characteristics, such as vegetation community and hydrological features or management practices (Schouten 2002). These were entered into the database as a single site. While each annual flux was represented as one entry in the database, for studies that reported several years of consecutive measurements, we have used the average annual flux estimate over the years. The following parameters were also extracted from each literature source and included in the database for further analysis: drainage status, nutrient status, mean water table level (WTL), peat depth, vegetation community, pH, and time since rewetting.

The following criteria were considered for inclusion in the database and in EF calculations:

1) Rewetted and near-natural sites reported in this study have a mean water table level of -30 cm or shallower in compliance with the Wetlands Supplement.
2) Only studies that reported annual Net Ecosystem Exchange (NEE) were included in the database. Studies that reported only soil respiration were excluded.
3) Studies were only included with a full year (12 months) of sampling.
4) The studies had to report an annual mean WTL for each annual/multi-year flux.
5) The studies had to indicate nutrient status (rich or poor, as per Rydin & Jeglum (2013)). In some cases, nutrient status was taken from other published studies at the same site.
6) In the case where fluxes from a site were reported in more than one study, we included the most complete and/or recent study to avoid double accounting.
7) All annual studies were treated equally and were given the same weighting regardless of the length of the monitoring period.
8) Care was taken to check for the independence of annual fluxes reported for the same sub-site type at the same peatland to avoid double accounting. If required, we contacted the authors to clarify the exact location of the experimental plots.

Following the Wetlands Supplement methodology, we used the atmosphere as a reference, so emissions are addressed as positive fluxes and removals as negative fluxes. In this paper, organic soils and peatlands were used as interchangeable terms. Based on collected annual GHG fluxes data, we derived CO_2 EF (t C ha^{-1} yr^{-1}), CH_4 EF (kg C ha^{-1} yr^{-1}), N_2O EF (kg N ha^{-1} yr^{-1}), and EF for fluvial C losses (t C ha^{-1} yr^{-1}) in each LUC with a 95 % confidence interval (CI).

In order to build a more robust baseline for EF from near-natural peatlands in Ireland, annual GHG fluxes from two Scottish peatlands were also used in EF calculations (Helfter *et al.* 2015, Levy & Gray 2015). For the same reason, annual GHG fluxes from two drained grassland sites were also used in EF calculations – nutrient-poor extensive grassland (Beetz *et al.* 2013) from north-western Germany and nutrient-rich intensive grassland site from the UK (Evans *et al.* 2016a). Unfortunately, we had to exclude annual GHG fluxes from Irish rewetted forestry sites from EF calculations as the two sites reported to date failed to achieve a higher water table level and the development of peatland species vegetation despite the restoration effort (Rigney *et al.* 2018). Instead, we used Tier 1 default EFs to calculate C emissions from the rewetted forestry LUC.

Carbon emissions and removals

For the purpose of this paper, we introduced a new term "combined emission factor" or $EF_{combined}$ that represents a sum of EFs for each gas in a LUC:

$$EF_{combined} = EF\ CO_2\text{-}C_{on\text{-}site} + EF\ C_{fluvial} + EF\ CH_4\text{-}C_{land} + EF\ CH_4\text{-}C_{ditch} \quad [1]$$

where $EF_{combined}$ = combined emission factor for organic soils in a LUC (t C ha^{-1} yr^{-1}), EF CO_2-$C_{on\text{-}site}$ = emission factor for on-site CO_2-C fluxes for organic soils in a LUC (t C ha^{-1} yr^{-1}), EF $C_{fluvial}$ = emission factor for fluvial C losses exported from a LUC (t C ha^{-1} yr^{-1}), EF CH_4-C_{land} = emission factor for CH_4-C_{land} fluxes from organic soils in a LUC (t C ha^{-1} yr-^{1}), EF CH_4-C_{ditch} = emission factor for CH_4-C_{ditch} fluxes from drainage ditches in drained organic soils in a LUC (t C ha^{-1} yr^{-1}).

CO_2-$C_{on\text{-}site}$ fluxes included direct on-site soil fluxes and the C exported via the removal of biomass for grassland. Methane fluxes from organic soils comprised fluxes from land areas (CH_4-C_{land}) and fluxes from the ditches in drained organic soils (CH_4-C_{ditch}). Published data in Ireland were insufficient to derive CH_4-C_{land} fluxes from drained forestry on peatlands and the CH_4-C_{ditch} fluxes in drained peatlands from all LUC. Methane fluxes from ditches can be omitted in the case of rewetted organic soil, where the ditches are assumed to disappear over time (IPCC 2014). $C_{fluvial}$ comprised indirect off-site fluvial C losses via DOC and, where possible, DIC, POC and open-water CO_2-C and CH_4-C evasion (gaseous evasion from the stream surface to the atmosphere). The published data were absent for fluvial losses from drained peat extraction sites, and drained forestry, as well as for rewetted nutrient-rich peatlands, rewetted afforested peatlands, and rewetted grassland. In these cases, we used the default Tier 1 values. Note, that Tier 1 EFs for fluvial losses only include DOC as EFs do not currently exist for the other fluvial components (IPCC 2014).

Annual total C emissions/removals from Irish peatlands were estimated using Equation 2:

$$C_{total} = \sum (A * EF_{combined}) \quad [2]$$

where C_{total} = annual C emissions/removals from all organic soils in Ireland (t C yr^{-1}), A = organic soils land area in a LUC (ha), $EF_{combined}$ = emission factor for this LUC (t C ha^{-1} yr^{-1}). In the case of drained forestry, $EF_{combined}$ also included living biomass and litter sinks extracted from Duffy *et al.* (2021).

Fluxes of N_2O from drained and rewetted organic soils are the result of the microbiological processes of nitrification and denitrification. N_2O EFs (kg N ha^{-1}yr^{-1}) presented in this paper comprised of N_2O fluxes due to N mineralisation caused by anthropogenic impacts (e.g., fertilisation). Finally, C emissions associated with horticulture peat and fuel peat combustion are reported under the energy sector and thus were not included in this paper.

RESULTS

Irish peatlands classification

The available data allowed us to disaggregate the drained nutrient-poor peat extraction category into industrial cutaway and domestic cutover sites (Figure 1). We were also able to stratify nutrient-poor grassland by shallow-drained and deep-drained sites. Here, we complied with the Wetlands Supplement (IPCC 2014), which defined deep-drained organic soils by a water table level of 30 cm or deeper below the ground surface and shallow-drained by a water table level above 30 cm. We were able to identify three previous land types in nutrient-poor rewetted peatlands (peat extraction, grassland, and forestry) and one in nutrient-rich rewetted peatlands (peat extraction). Figure 1 represents the land use categories of peatlands in Ireland with available annual GHG flux data. Note that not all categories had sufficient annual GHG flux data to derive suitable EFs.

Data summary

The GHG flux database incorporates 18 studies with 292 annual fluxes reported and covers 11 LUCs (Table 1). Since the last assessment of Irish peatland GHG emissions (Wilson *et al.* 2013), the number of monitored peatland sites has increased from 5 to 14. The number of sub-sites increased from 12 to 54, and the number of annual fluxes reported nearly quadrupled from 33 to 124 for CO_2 and from 28 to 95 for CH_4 (Table 1). Annual fluxes of N_2O were not reported previously (Wilson *et al.* 2013), whereas we are able to report 60 annual fluxes here.

DOC was previously reported only for a near-natural, Atlantic blanket bog for two years (with an additional four years of modelled data) (Koehler *et al*. 2011). In this paper, we were able to report fluvial losses (including DOC, DIC, POC, and CO_2 and CH_4 evasion where available) from 13 peatlands across Ireland. The distribution of GHG measurements is weighted toward the midlands region, home to the largest area of oceanic raised bogs, with fewer measurements on blanket bogs (Figure 2).

GHG fluxes from Irish peatlands

Near-natural peatlands

Near-natural peatlands were a net CO_2 sink, although ranged from a small CO_2 source of 67 g C m^{-2} y^{-1} (Renou-Wilson *et al.* 2011) to a CO_2 sink of -114 g C

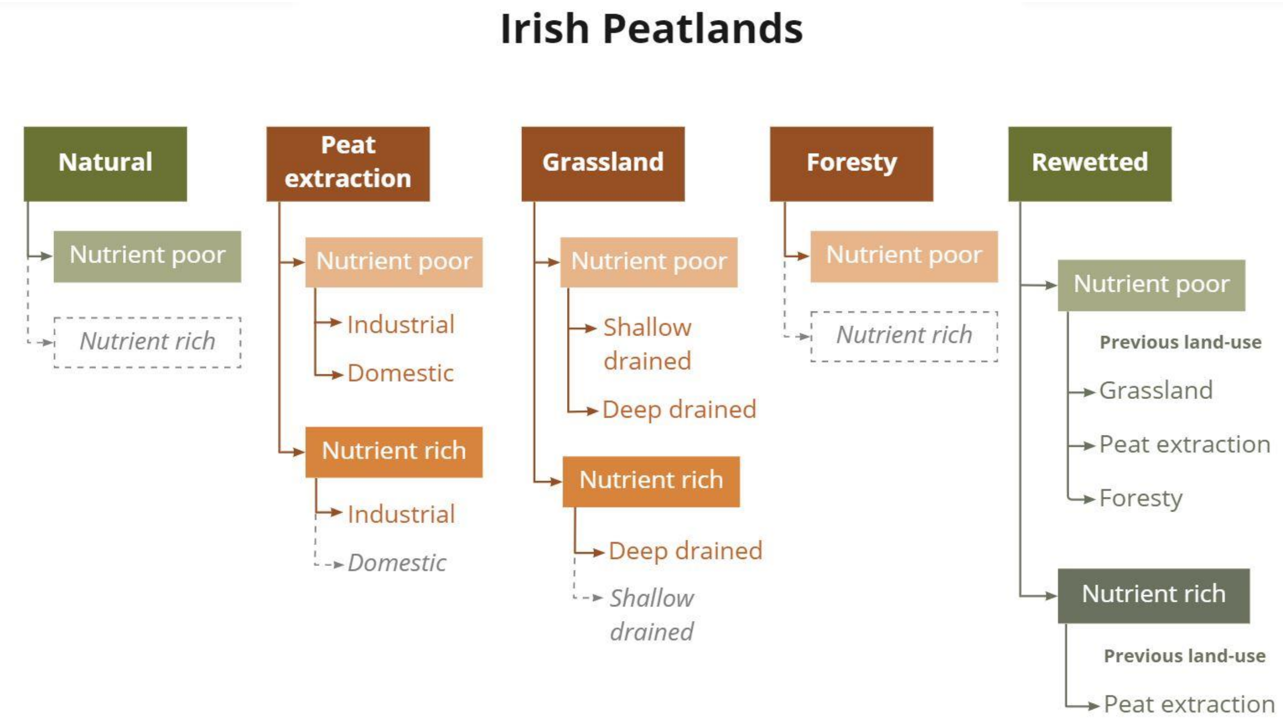

Figure 1. Land use classification used for Irish country-specific emission factor (EF) calculations. Green cells represent rewetted and near-natural peatlands, and brown cells represent drained peatlands. Brighter and lighter colours represent nutrient-rich and nutrient-poor peatlands respectively. Note that categories in italics lacked measured GHG fluxes and not all categories had sufficient annual GHG flux data to derive suitable EFs.

Table 1. Number of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) flux measurements and fluvial loss data points in Irish peatlands by land use category (LUC) and greenhouse gas (GHG) type. Data include publications up to 2022.

Land use category	Nutrient status	No. annual fluxes			No. sub-sites			No. peatland locations		
Greenhouse Gas		CO_2	CH_4	N_2O	CO_2	CH_4	N_2O	CO_2	CH_4	N_2O
Near-natural	poor	14	10	0	5	7	0	3	3	0
Grassland	poor	6	6	4	3	1	1	1	1	1
Grassland deep drained	rich	1	1	1	1	1	1	1	1	1
Industrial peat extraction	poor	6	4	4	3	2	2	2	2	2
Industrial peat extraction	rich	6	6	4	2	2	1	2	2	1
Domestic peat extraction	poor	9	7	4	4	3	1	3	3	1
Forestry	poor	14	0	0	8	0	0	1	0	0
Rewetted. Peat extraction	poor	41	36	24	13	13	5	4	4	2
Rewetted. Grassland	poor	4	4	4	2	2	2	1	1	1
Rewetted. Forestry	poor	7	7	7	7	7	7	2	2	2
Rewetted. Peat extraction	rich	16	13	8	6	5	2	2	2	1

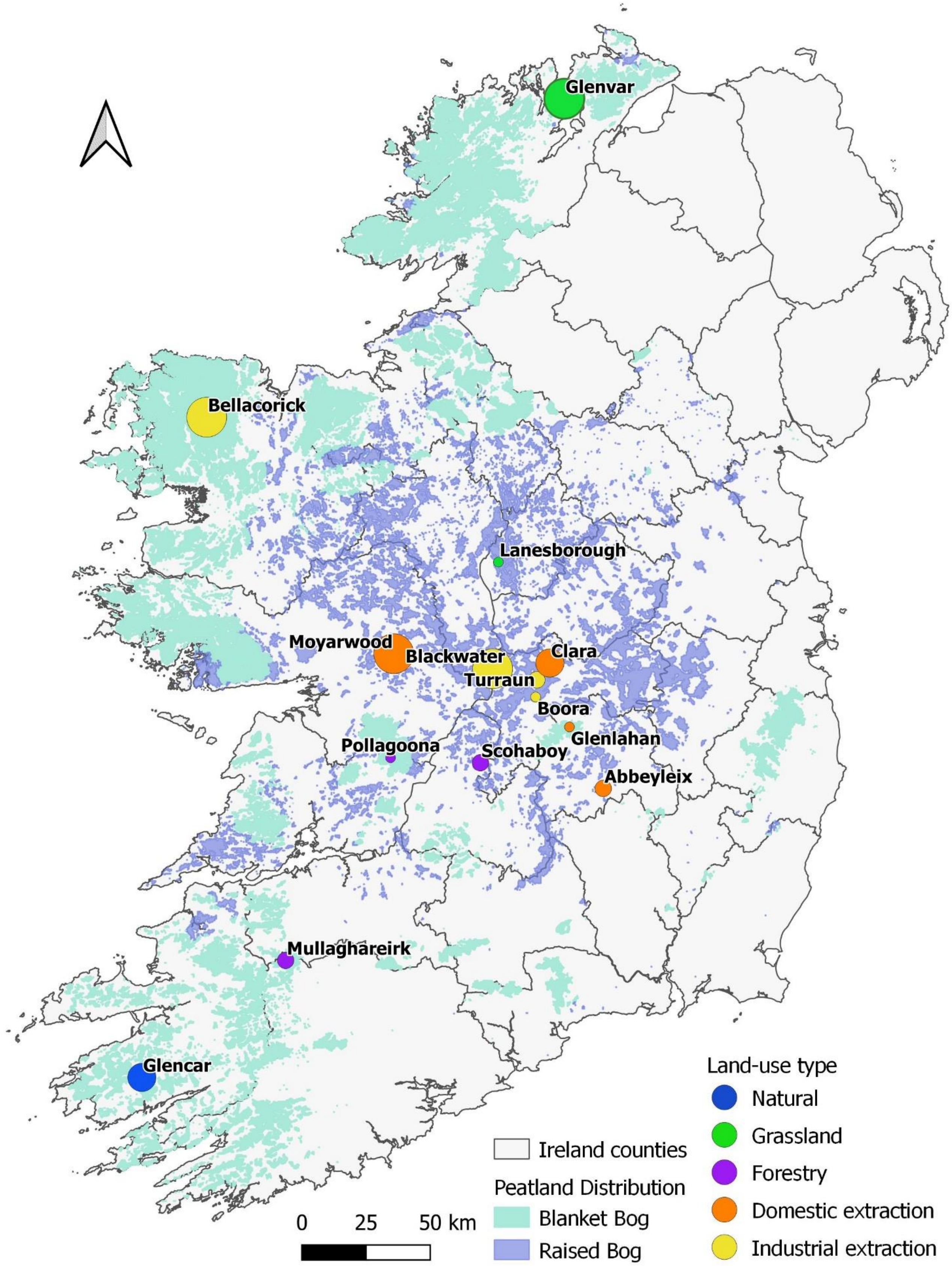

Figure 2. Map of Ireland showing the distribution of bogs (Connolly & Holden 2009) and locations of the study sites. Size of the icon represents the relative number of annual measurements (CO_2-C, CH_4-C, N_2O-N and fluvial fluxes combined) from this location.

m^{-2} y^{-1} (Levy & Gray 2015) (Figure 3). The most studied site is a blanket bog in Co. Kerry, which was monitored for almost a decade (Laine *et al.* 2006, Koehler *et al.* 2011, Sottocornola & Kiely 2010, McVeigh *et al.* 2014) and reported inter-annual C fluxes supported by different measurement methodologies (both EC and static chambers) (Laine *et al.* 2006). As expected, the near-natural peatlands were a net annual CH_4 source (Figure 4) and also lost C via surface runoff (Koehler *et al.* 2011, Regan *et al.* 2020). The EFs of CO_2 (-0.33 t C ha^{-1} y^{-1}), CH_4 (54.7 kg C ha^{-1} y^{-1}) and fluvial losses (0.17 t C ha^{-1} y^{-1}) for near-natural peatlands were calculated based on three near-natural peatlands in Ireland and two near-natural peatlands in Scotland (Table 2, Table 3).

Peat extraction

The CO_2 and CH_4 fluxes were disaggregated between domestic and industrial peat extraction (Figure 3 and Figure 4). The nutrient-poor domestic peat extraction sites were a net annual CO_2 source that ranged between 108 g C m^{-2} y^{-1} and 203 g C m^{-2} y^{-1} (Wilson *et al.* 2015, Regan *et al.* 2020) and a small CH_4 source (Renou-Wilson *et al.* 2011, 2022).

The studies showed that nutrient-rich industrial peatlands had greater CO_2 and lower CH_4 fluxes than nutrient-poor industrial sites. Nutrient-rich industrial peat extraction sites reported annual CO_2 fluxes between 111 g C m^{-2} y^{-1} (Renou-Wilson *et al.* 2019) and 304 g C m^{-2} y^{-1} (Wilson *et al.* 2015). The nutrient-poor industrial cutaway peatlands reported annual fluxes of CO_2 between 23 and 189 g C m^{-2} y^{-1} (Wilson *et al*. 2015, 2016b). Annual CH_4 fluxes were -0.03 g C m^{-2} y^{-1} for nutrient-rich peatlands and net zero for nutrient-poor peatlands (Wilson et al 2009, Renou-Wilson *et al.* 2019).

Grassland

Annual fluxes from nutrient-poor grassland have been investigated under different management conditions and drainage classes (Renou-Wilson *et al.* 2014, 2016). These studies showed the significant impact of biomass export and water table level on C balance. The nutrient-rich deep-drained grassland sites showed the greatest net annual CO_2 fluxes together with biomass (584 g C m^{-2} y^{-1}) (Renou-Wilson *et al.* 2014). The studies indicated that drained organic soils under grassland are a CH_4 source for shallow drained sites (1.2–1.5 g C m^{-2} y^{-1}) and net zero for deep-drained sites (Renou-Wilson *et al.* 2014, 2016).

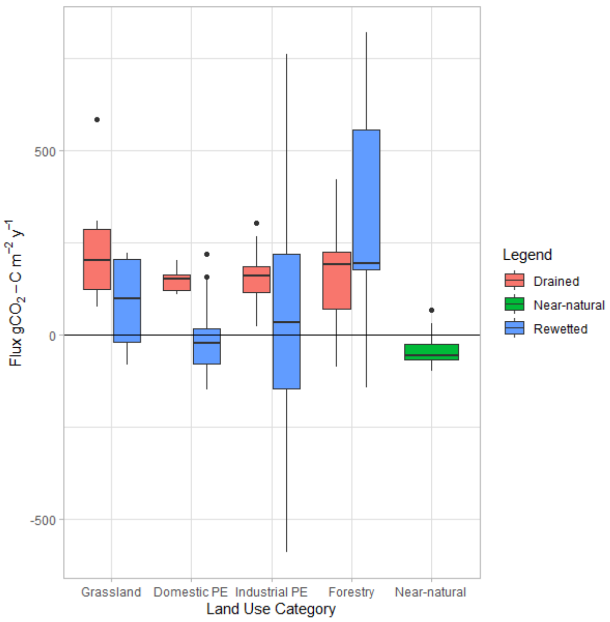

Figure 3. Boxplots of annual carbon dioxide (CO_2-C) fluxes (g C m^{-2} y^{-1}) from Irish peatlands. Boxplots show median flux (line) with 25th to 75th interquartile range as the extent of the coloured box. Error lines denote the range of values. Positive values indicate emissions from the soil and negative values indicate removal from the atmosphere. PE = Peat Extraction.

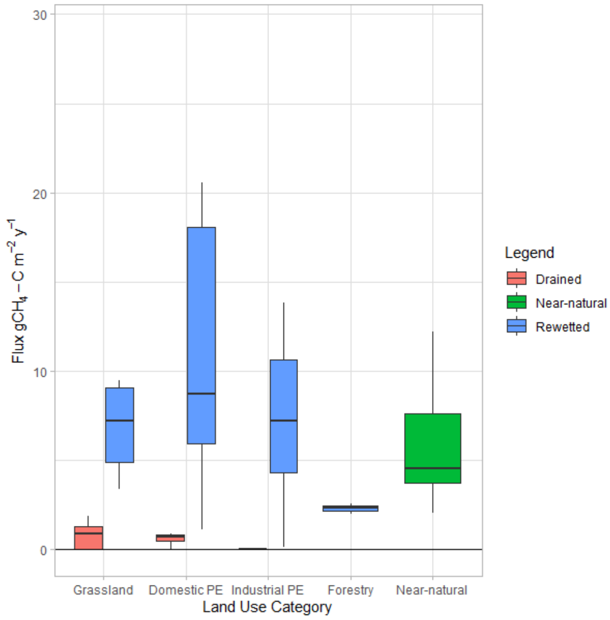

Figure 4. Boxplot of annual methane (CH_4-C) fluxes (g C m^{-2} y^{-1}) from Irish peatlands. Boxplots show median flux (line) with 25th to 75th interquartile range as the extent of the coloured box. Error lines denote the range of values. Positive values indicate emissions from the soil and negative values indicate removals from the atmosphere. PE = Peat Extraction.

Table 2. Carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) Tier 1 values and proposed Irish national emission factors (EFs) for organic soils and their 95 % confidence intervals (values in brackets). Default Tier 1 EF values are taken from Tables 2.1, 2.3, 2.5 and 3.3 in the 2013 IPCC Wetlands Supplement. NM = not measured.

<table>
<tr><th>Peatland land use type</th><th>Nutrient status</th><th colspan="2">CO_2 EF (t C ha^{-1} y^{-1})</th><th colspan="2">CH_4 EF (kg C ha^{-1} y^{-1})</th><th colspan="2">N_2O EF (kg N ha^{-1} y^{-1})</th></tr>
<tr><td></td><td></td><td>Tier 1</td><td>Irish</td><td>Tier 1</td><td>Irish</td><td>Tier 1</td><td>Irish</td></tr>
<tr><td>Industrial cutaway</td><td>Nutrient-poor</td><td rowspan="3">2.8 (1.1 – 4.2)</td><td>1.21 (0.4 – 2)</td><td rowspan="3">4.6 (1.2 – 8.3)</td><td>0</td><td rowspan="3">0.3 (0 – 0.6)</td><td>0</td></tr>
<tr><td>Industrial cutaway</td><td>Nutrient-rich</td><td>2.18 (0.86 – 3.5)</td><td>-0.3 (-0.8 – 0.3)</td><td>0</td></tr>
<tr><td>Domestic cutover</td><td>Nutrient-poor</td><td>1.59 (1.2 – 2.0)</td><td>4.6 (-0.4– 9.6)</td><td>0</td></tr>
<tr><td>Grassland</td><td>Nutrient-poor</td><td>5.3 (3.7 – 6.9)</td><td>1.30 (0.04 – 2.55)</td><td>1.4 (0.5 – 2.1)</td><td>8.82 (2.63 – 15.02)</td><td>4.3 (1.9 – 6.8)</td><td>0</td></tr>
<tr><td>Grassland, deep-drained</td><td>Nutrient-rich</td><td>6.1 (5.0 – 7.3)</td><td>5.08 (3.6 – 6.57)</td><td>12 (1.8 – 21.8)</td><td>-0.75 (-2.2 – 0.72)</td><td>8.2 (4.9 – 11)</td><td>1.6</td></tr>
<tr><td>Forestry</td><td>Nutrient-poor</td><td>2.6 (2.0 – 3.3)</td><td>1.68</td><td>1.9 (-0.5 – 4.2)</td><td>NM</td><td>2.5 (-0.6 – 6.1)</td><td>NM</td></tr>
<tr><td>Near-natural</td><td>Nutrient-poor</td><td rowspan="3">-0.23 (-0.6 – 0.2)</td><td>-0.33 (-0.8 – 0.1)</td><td rowspan="3">92 (3 – 445)</td><td>54.7 (22.4 – 86.9)</td><td rowspan="3">0</td><td>NM</td></tr>
<tr><td>Rewetted, peat extraction</td><td>Nutrient-poor</td><td>-0.23 (-0.8 – 0.4)</td><td>79.8 (50.4 – 109)</td><td>0</td></tr>
<tr><td>Rewetted, grassland</td><td>Nutrient-poor</td><td>0.85 (-1.6 – 3.3)</td><td>68.1 (20.9 – 115.2)</td><td>0</td></tr>
<tr><td>Rewetted, peat extraction</td><td>Nutrient-rich</td><td>0.5 (-0.7 – 1.7)</td><td>3.22 (1.1 – 5.4)</td><td>216 (0 – 856)</td><td>117.9 (31.9 – 203.8)</td><td></td><td>0</td></tr>
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Table 3. Emission factors (EFs) for fluvial ($C_{fluvial}$) carbon losses (t C ha^{-1} y^{-1}) for drained and rewetted peatlands in Ireland. Standard deviation is given when fluvial losses were measured at > one location.

Peatland land use type	Nutrient status	No. peatlands	No. annual fluxes	$C_{fluvial}$ (t C ha^{-1} y^{-1})
Peat extraction (domestic)	Nutrient-poor	1	1	0.16
Grassland	Nutrient-poor	1	2	0.37
Grassland, deep-drained	Nutrient-rich	1	1	0.6
Near-natural	Nutrient-poor	4	17	0.17 ± 0.13
Rewetted, peat extraction	Nutrient-poor	2	3	0.11 ± 0.01

Rewetted peatlands

The rewetted peat extraction peatlands are the most monitored peatland LUC in Ireland (Table 1). The CO_2 annual fluxes varied between -588 g C m^{-2} y^{-1} for a nutrient-poor site (Wilson *et al.* 2016b) and 760 g C m^{-2} y^{-1} for a nutrient-rich site (Wilson *et al.* 2007). All the sites were a CH_4 source (Figure 4) and lost C via fluvial pathways (Swenson *et al.* 2019).

Carbon fluxes from rewetted grassland were reported from a single study on one site (Table 1). The study demonstrated that CO_2 and CH_4 fluxes decreased after a shift of management from grazed to ungrazed (Renou-Wilson *et al.* 2016).

Carbon fluxes from rewetted forestry sites are based on a one year-study on a former afforested blanket bog site and a former afforested raised bog site (Rigney *et al.* 2018). The study showed that both sites were a CO_2 source (Figure 3). Only one sub-site (*Cladonia-Calluna*, Pollagoona, Co. Clare) acted as a strong sink (-143 g C m^{-2} y^{-1}). All the sites were a net annual CH_4 source between 0.54 to 4.8 g C m^{-2} y^{-1} (Figure 4).

Country-specific emission factors

The proposed Irish country-specific CO_2, CH_4 and N_2O EFs were compared against Tier 1 EFs (Table 2). Values reported for fluvial loss included DOC, DIC, POC, and CO_2 and CH_4 evasion, where available (Table 3). The Wetlands Supplement reports only DOC, therefore, we did not make a comparison with Tier 1 EFs. Where it was not possible to propose an Irish EF for fluvial losses, we used the Tier 1 value to calculate total emissions, namely 0.31 t C ha^{-1} y^{-1} for drained peatlands and 0.24 t C ha^{-1} y^{-1} for rewetted peatlands.

National peatland carbon emissions/removals

The distribution of peatlands by LUC is a matter of on-going research in Ireland and has been best estimated here by gathering information from relevant institutions dealing with each LUC individually (Figure 5). Ireland is unique in that the agricultural land on peatlands is predominately represented by grassland (332,000 ha, Duffy *et al.* 2021), while the proportion of cropland is negligible (1,235 ha, Donlan *et al.* 2016). Current official estimations demonstrate that only a small proportion of degraded peatlands have been rewetted. Due to the absence of data on the estimated cover of rewetted grassland, we were not able to calculate the total emissions from this LUC.

All EFs (t C ha^{-1} y^{-1}) were combined into a single combined C emission factor for each LUC (Table A1

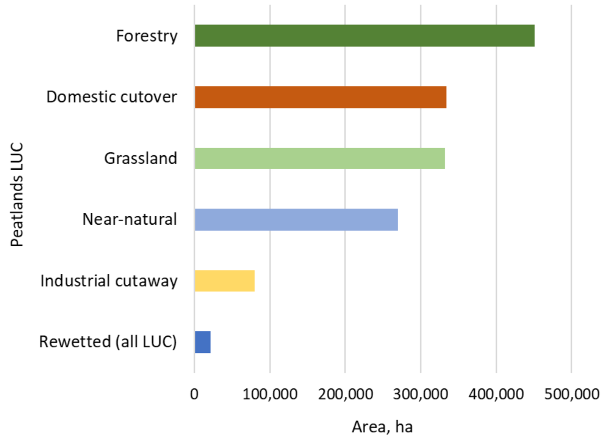

Figure 5. Proportion of peatlands in Ireland by land use category (LUC). Data sources: peatland areas for forestry, grassland and industrial peat extraction are taken from Duffy *et al*. (2021). The domestic cutover area is calculated as a subtraction from the total area of drained and near-natural Irish peatlands (Connolly & Holden 2009). The area of near-natural peatlands is taken from Wilson *et al.* (2013). The area of rewetted nutrient-rich peat extraction sites is provided by Bord na Móna. Rewetted forestry area is taken from Delaney & Murphy (2012). The area under rewetted nutrient-poor peat extraction is calculated as a substruction of rewetted areas mentioned above from the total area of rewetted peatlands (Wilson *et al*. 2013).

in the Appendix). Combined EFs, together with the best available areal estimates, were used to calculate the total C emissions/removals from Irish peatlands (Table 4). In total, Irish peatlands are estimated to emit 1.9 Mt C y^{-1} to the atmosphere with an uncertainty range of 0.4–3.4 Mt C y^{-1}. This figure does not contain annual C emissions from peat related to energy production and horticultural extraction.

Drained grassland exhibited the greatest annual C emissions among all LUCs. An estimated area of 332,000 ha of grassland on organic soils is currently used in Ireland's NIR (Duffy *et al*. 2021) and probably represents a considerable underestimation given the proposed estimation of 420,000 ha of grassland on organic soils by Green (2020). Carbon emissions from drained peat extraction sites using our proposed EFs amount to around 0.75 Mt C y^{-1}, which is more than one-third of the total emissions, with the vast majority associated with domestic peat extraction. The relatively high C emissions from domestic cutover sites are due to the large area involved; the second greatest area after forestry (Figure 5). Afforested drained peatlands were a C source despite the C removals by the living biomass (trees) and litter. The data showed that extracted peatlands became a small net C sink after rewetting despite CH_4 emissions and fluvial losses.

DISCUSSION

Implications of proposed Irish emission factors

In this paper we proposed country-specific level of EFs for on-site CO_2, CH_4 and, in some cases, N_2O fluxes and off-site fluvial C losses for Ireland's drained and rewetted peatlands (i.e. 'managed wetlands'). Our proposed EFs could be expected to significantly improve the accuracy in emissions reporting compared to the default level currently presented in the Wetlands Supplement and could form the basis for Tier 2 EFs reporting from Irish peatlands.

Peat extraction

In Ireland, the NIR (Duffy *et al.* 2021) amalgamates industrial and domestic peat extraction LUCs and employs a CO_2 EF of 1.68 t C ha^{-1} y^{-1} reported in Wilson *et al.* (2015). Here, we report a lower CO_2 EF of 1.59 t C ha^{-1} y^{-1} for all peat extraction sites. While this value could be adopted for domestic peatlands (our results indicate a CO_2 EF of 1.59 t C ha^{-1} y^{-1} for this LUC), our study showed a marked difference between nutrient-poor and nutrient-rich CO_2 EFs for industrial peatlands (1.21 t C ha^{-1} y^{-1} and 2.18 t C ha^{-1} y^{-1} respectively). Currently, the area under industrial peatland is reported without disaggregation between these categories (Duffy *et al.* 2021). Thus, reported national emissions may misrepresent C emissions

Table 4. Combined total carbon emission factor (t C $ha^{-1}y^{-1}$), including carbon dioxide (CO_2), methane (CH_4) fluxes and fluvial losses, as well as biomass sinks; area (ha), total emissions/removals (t C y^{-1}) and uncertainty range (95 % Confidence intervals) from the main peatland land use categories (LUC) in Ireland.

LUC	Combined total emission factor (t C ha^{-1} y^{-1})	Area (ha)	Emissions (t C y^{-1})	Lower CI	Upper CI
Near-natural	-0.11 (±0.26)	269,270	-29,879	-109,628	49,871
Grassland	3.09 (±1.34)	332,000	1,026,630	522,080	1,531,181
Domestic peat extraction	1.77 (±0.87)	334,259	529,238	265,002	919,475
Industrial peat extraction	1.93 (±0.84)	80,000	154,176	78,196	230,156
Forestry	0.29 (±0.89)	450,940	130,736	-323,579	585,051
Rewetted (peat extraction, poor)	-0.05 (±0.19)	17,826	-866	-4,682	2,950
Rewetted (forestry)	0.10 (±0.24)	3,174	324	-539	1,187
Rewetted (grassland)	1.16 (±0.41)	0	0	0	0
Rewetted (peat extraction, rich)	3.58 (±1.76)	6,169	22,098	9,817	34,378
Total			1,895,458	436,667	3,354,248

from industrial peatlands. Future mapping of industrial peatlands should include nutrient status to offer a more accurate estimation of C emissions.

Against the Tier 1 CH_4 EF of 4.6 kg C ha^{-1} y^{-1} for peat extraction sites, our CH_4 EF is lower for industrial peat extraction sites (Table 2). The Irish industrial peatlands mostly consisted of bare peat sites, which resulted in a lower CH_4 EF value, while the Tier 1 EF combined peat extraction LUCs with various vegetation cover.

Grassland

For nutrient-poor grassland on organic soils, our CO_2 EF of 1.30 t C ha^{-1} y^{-1} is lower than the Tier 1 CO_2 EF of 5.3 t C ha^{-1} y^{-1} for the same category (Table 2). It is also lower than the EF of 3.6 t C ha^{-1} y^{-1} used by the UK for extensive grassland on nutrient-poor peatlands (Evans *et al.* 2017). The majority of studies for grassland in the Wetlands Supplement originated from Germany where grasslands have more intensive management practise than in Ireland (Renou-Wilson *et al.* 2014, IPCC 2014). Our CO_2 EF (5.08 t C ha^{-1} y^{-1}) for deep-drained nutrient-rich grassland are similar to both the Tier 1 value of 6.1 t C ha^{-1} y^{-1} and the UK's CO_2 EF of 6.4 t C ha^{-1} y^{-1}.

Our proposed CO_2 EF value suggests that currently reported emissions from nutrient-poor grassland could, in fact, decrease significantly and this would have considerable implications in terms of LULUCF reporting. Furthermore, the current area estimation is not disaggregated between nutrient-rich and nutrient-poor grassland, with the latter being more widespread. Thus, more accurate mapping could improve the robustness of national emissions reporting from this LUC. Renou-Wilson *et al*. (2014) also showed that grassland where the annual water table level is maintained within 30 cm of the surface, could significantly contribute to reducing emissions. Considering the area of organic soils under grassland in Ireland, management practices could provide a large reduction of C emissions at the national level, as proposed in the UK (Evans *et al*. 2021). For the development of Tier 2 EFs for grassland, it is also important to incorporate country-specific data on land use intensity and distinguish between extensive, intensive, and rough grazing grassland (IPCC 2014).

Compared to the default CH_4 EF of 1.4 kg C ha^{-1} y^{-1}, our estimated CH_4 EF of 8.82 kg C ha^{-1} y^{-1} for nutrient-poor grassland is much greater. This is likely due to the Irish estimates being mainly based on shallow-drained sites in a temperate oceanic climate, while the grassland sites used in the Tier 1 calculations are mainly comprised of deep-drained sites from countries with continental climates. The UK inventory reported an even greater CH_4 value of 54.8 kg C ha^{-1} y^{-1} for nutrient-poor shallow-drained grassland (Evans *et al.* 2017).

Both our CH_4 EF and N_2O EF for deep-drained nutrient-rich grassland were far lower than the equivalent Tier 1 but these values lack robustness, being based on one-year measurement from a single site (Renou-Wilson *et al.* 2014).

Forestry on peatlands

Our proposed soil CO_2 EF of 1.68 t C ha^{-1} y^{-1} for drained peatlands under forestry is lower than the default Tier 1 EF of 2.6 t C ha^{-1} y^{-1} (Table 2) but similar to the UK's CO_2 EF of 2 t C ha^{-1} y^{-1} from drained forested land (Evans *et al.* 2017) and the soil CO_2 EF of 1.6 t C ha^{-1} y^{-1} utilised in Ireland's NIR (since 2022). The latter replaces the previously reported value of 0.59 t C ha^{-1} y^{-1} (Duffy *et al.* 2021, 2022) and is likely to substantially reduce the C sink potential of this LUC.

Rewetted peatlands

Our proposed CO_2 EF for nutrient-poor rewetted peat extraction sites of -0.23 t C ha^{-1} y^{-1} is similar to the default Tier 1 CO_2 EF for nutrient-poor rewetted peatlands (Table 2). It is important to note that the Tier 1 EF combines data from natural and rewetted sites and does not differentiate sites by previous land use. Rewetted peatlands exhibit wide variability in EFs depending on the previous land use. This results in considerable uncertainty when these EFs are averaged for CO_2 EF for all rewetted peatlands. It would be more prudent to report them separately as recommended in other peatland-rich jurisdictions (Bianchi *et al.* 2021).

In the UK, a CO_2 EF value of -0.6 ± 0.5 t C ha^{-1} y^{-1} is employed for rewetted nutrient-poor sites and contains data only from the sites with relevant climate conditions and vegetation types (Evans *et al.* 2017). As the UK has a similar climate to Ireland, this much greater sink value demonstrates the potential of rewetting to significantly reduce CO_2 emissions and create optimal conditions for CO_2 sequestration in nutrient-poor Irish peatlands, especially in former peat extraction sites. Conversely, our proposed CO_2 EF of 3.22 t C ha^{-1} y^{-1} for nutrient-rich sites (represented by former peat extraction sites) suggests that, for this type of rewetted peatlands, rewetting actions alone would not be sufficient to avoid CO_2 emissions. This has direct implications for current and future rewetting programmes, which should prioritise nutrient-poor extraction sites.

The majority of industrial peat extraction sites in Ireland are managed by Bord na Móna, which is obliged to rehabilitate these sites under the Integrated Pollution Control licenses issued by the Environmental Protection Agency. However, only a few areas have been successfully rewetted in terms of minimising GHG emissions (Renou-Wilson *et al*. 2019). In addition, the recent Peatlands Climate Action Scheme (funded by the Department of the Environment, Climate and Communications (DECC)) requires Bord na Móna to rewet at least 33,000 ha of industrial cutaway with the aim to avoid 3.2 Mt of CO_2 emissions by 2050 (DECC 2021a).

The rewetted grasslands (nutrient-poor) CO_2 EF is based on a single experimental site, which contained both grazed and ungrazed management (Renou-Wilson *et al.* 2016). Our proposed CO_2 EF for this category is greater than the Tier 1 CO_2 EF (0.85 ± 1.2 vs -0.23 ± 0.4 t C ha-1 y-1) for the closest analogue category in the Wetlands Supplement. The experiment demonstrated a reduction in CO_2 emissions compared to drained grassland, but the site remains a C source overall. Rewetting actions may offer the potential to significantly reduce CO_2 emissions from agricultural land on organic soils (Renou-Wilson *et al.* 2016, Hemes *et al.* 2019). Currently, there are no reported rewetted grassland areas in Ireland. Although the "Ag Climatise" Roadmap introduced by the Department of Agriculture, Food and the Marine (DAFM) and the "Climate Action Plan" by the Department of the Environment, Climate and Communications provide potential routes to reduce C emissions through the maintenance of a shallow water table and the promotion of lower livestock stocking densities on grassland under organic soils (DAFM 2020, DECC 2021b).

Our proposed CO_2 EF of 3.22 ± 2.7 t C ha^{-1} y^{-1} for nutrient-rich rewetted peatlands sites is much greater than the Tier 1 EF of 0.5 ± 1.2 t C ha^{-1} y^{-1} (Table 2). This is not surprising since the wide variability of outcomes from nutrient-rich peatlands has been suggested earlier (IPCC 2014, Evans *et al.* 2017). Nutrient-rich rewetted cutaway peatlands may be on a trajectory toward fen development rather than towards a nutrient-poor raised bog (Renou-Wilson *et al.* 2019). In this case, additional management would be needed if the aim is to reduce overall emissions, over biodiversity: this could include phosphorus fertilisation (Quinty *et al*. 2020), phenolic enrichment (Alshehri *et al*. 2020) and/or peatland species transfer (Hugron *et al.* 2020).

Uncertainties and information gaps

While increased data on annual GHG fluxes from Irish peatlands has become available since the last review (Wilson *et al.* 2013), significant gaps and uncertainties remain. Firstly, GHG studies in Ireland are limited temporarily or geographically, especially for land use categories, such as grassland and forestry. Grassland is one of the largest land use categories (Duffy *et al.* 2021), however, the nutrient-rich grassland EF is based on a single 12-month study (Renou-Wilson *et al.* 2014) and the four-year study on the nutrient-poor grassland was from only one site in Co. Donegal (Renou-Wilson *et al*. 2016). The estimation of C emissions from drained forestry is based only on one study (but 8 sites), which provides only annual CO_2 fluxes (Jovani-Sancho *et al*. 2021).

Secondly, to increase the accuracy linked with EF calculations and total C emissions and therefore provide evidence-based peatland management policy, long-term monitoring is essential for all peatland land use categories (Wilson *et al*. 2016b, Swenson *et al.* 2019). For rewetted sites, it is important to account for inter-annual variation and to monitor long-term changes in vegetation and associated C dynamics (Rigney *et al.* 2018, Swenson *et al.* 2019). Further monitoring of drained peatlands is required to provide a baseline for C emissions/removals from rewetted/restored peatlands and set proper targets for potentially larger-scale peatland projects.

Renou-Wilson *et al.* (2016) highlights the necessity to promote long-term monitoring research of organic soils under grassland to examine the contribution of raised water table level on C dynamics, and we again highlight the need for capacity building to ensure that these long-term programmes are properly funded. Currently, research is underway to provide C emissions/removals data from grasslands on organic soils with a focus on managing the water table as part of the National Agricultural Soil Carbon Observatory (Teagasc 2021).

Thirdly, the existing monitoring sites in Ireland have limited spatial diversity. Despite GHG fluxes reported from different ecotopes, the sub-sites are often located within the same peatland location (Wilson *et al.* 2016b, Swenson *et al.* 2019). Due to a lack of available long-term monitoring of drained sites, past GHG studies have tended to use sub-sites with low water table levels within rewetted peatlands (Wilson *et al*. 2009, 2015, 2016b, Renou-Wilson *et al*. 2011, 2019, Regan *et al*. 2020). Evans *et al.* (2017) developed a methodology where weighting is assigned to EFs depending on the number of years of monitoring and geographical location of the sites. A greater weighting is given to longer monitoring periods and more geographically spread sites. This, however, requires more studies distributed across the range of peatland distribution.

Fourthly, to cover all EFs from the IPCC methodologies (off-sites, ditches, etc.), different components of the C balance from peatlands should be available. Fluvial losses from Irish peatlands have been found to be a significant component of the total C balance (Koehler *et al.* 2011, Swenson *et al.* 2019, Regan *et al.* 2020). Fluvial losses combine indirect emissions via surface runoff, mainly DOC and POC and GHG fluxes from open water within the site (Evans *et al.* 2016b). In our analysis, the fluvial losses were measured only from two natural, two drained grasslands and two rewetted peat extraction peatlands (Koehler *et al.* 2011, Renou-Wilson *et al.* 2014, Swenson *et al.* 2019, Regan *et al.* 2020). Data on fluvial losses for drained peat extraction sites are conspicuously absent. Furthermore, GHG fluxes from ditches in drained peatlands, particularly CH_4, are likely to be substantial (Peacock *et al.* 2021). These data are not currently available in Ireland, however, CH_4 fluxes from ditches are required for Tier 1 and Tier 2 EF calculations (IPCC 2014).

Finally, our analysis (not presented here) did not support the disaggregation by peat depth. The limited studies to date suggest that peat depth has little impact on short-term annual emissions from drained peatlands, and both shallow and deep peat sites emit at the same rate (IPCC 2014, Leiber-Sauheitl *et al.* 2014, Evans *et al.* 2017). However, this should be fully investigated in new research.

In moving toward Tier 2 level reporting in Ireland, studies need to provide more empirical GHG data, as well as ancillary measurements, such as land use practices, peat depth, time since rewetting, previous land use and drainage level to help predict C emissions (Tier 3) (Premrov *et al.* 2021). Furthermore, national EFs are only useful if there are associated with robust areal data and thus both uncertainties must be reduced concurrently. With this in mind, it is in the interest of the Irish government to urgently remedy the lack of repository geographical information on both public and private peatland rewetting projects.

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AUTHOR CONTRIBUTIONS

TM and FRW conceived of the presented idea, TM supervised the project. EA created the GHG database and performed the calculation under FRW and DW supervision. EA wrote the manuscript with support from TM, FRW and DW. All authors provided critical feedback and helped shape the methodology, analysis and manuscript.

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Appendix

Table A1. Combined total carbon emission factor variables (t C $ha^{-1}y^{-1}$) with 95 % confidence intervals (values in brackets). The CH_4 EF includes both CH_{4_land} and CH_{4_ditch} and is calculated by using Equation 2.6 in IPCC (2014). Grassland CO_2 EF includes biomass export, the drained forestry combined EF includes trees biomass and litter sink (Duffy *et al.* 2021). Default Tier 1 EF values are represented by * and are taken from Tables 2.2, 2.3, 2.4, 3.2 and 3.3 in the 2013 IPCC Wetlands Supplement.

LUC	CO_2 EF (t C ha^{-1} y^{-1})	CH_4 EF (t C ha^{-1} y^{-1})	Fluvial losses EF (t C ha^{-1} y^{-1})	Combined total emission factor (t C ha^{-1} y^{-1})
Near-natural	-0.33 (±0.62)	0.05 (±0.04)	0.17 (±0.13)	-0.11 (±0.26)
Grassland	2.56 (±2.24)	0.04	0.50 (±2.17)	3.09 (±1.34)
Domestic peat extraction	1.59 (±0.39)	0.02	0.16	1.77 (±0.87)
Industrial peat extraction	1.60 (±0.88)	0.02	0.31 (0.18–0.46)*	1.93 (±0.84)
Forestry	1.68	0.01*	0.31 (0.18–0.46)*	0.29 (±0.89)
Rewetted (peat extraction, poor)	-0.23 (±1.12)	0.08 (±0.05)	0.11 (±0.1)	-0.05 (±0.19)
Rewetted (forestry)	-0.23*	0.09*	0.24 (0.14–0.36)*	0.10 (±0.24)
Rewetted (grassland)	0.85 (±1.77)	0.07 (±0.03)	0.24 (0.14–0.36)*	1.16 (±0.41)
Rewetted (peat extraction, rich)	3.22 (±2.69)	0.12 (±0.10)	0.24(0.14–0.36)*	3.58 (±1.76)