



Examining challenges and uncertainties associated with using water table management to reduce greenhouse gas emissions from grassland peat soils

Hilary Pierce^{a,b}, Owen Fenton^c, Eve Daly^{a,*}, Mark G. Healy^d, Patrick Tuohy^b

^a School of Natural Sciences, Earth and Life, Ryan Institute, College of Science and Engineering, University of Galway, Ireland

^b Teagasc, Animal and Grassland Research and Innovation Centre, Moorepark, Fermoy, Co. Cork, Ireland

^c Teagasc, Environment Research Centre, Johnstown Castle, Co. Wexford, Ireland

^d Civil Engineering and Ryan Institute, College of Science and Engineering, University of Galway, Ireland

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ABSTRACT

Countries with significant areas of grassland on organic soils must accurately estimate the extents of these lands to estimate greenhouse gas (GHG) emissions from them. These areas are often targeted for management change to reduce emissions reported under the Land Use, Land Use Change and Forestry (LULUCF) sector in national GHG emission inventories. The present study aims to assess the extent of grassland on organic soils across the European Union (EU) and their associated GHG emissions and utilises a systematic review process to quantify the potential effectiveness of efforts to raise the water table level on such lands. Additionally, using Ireland as a case study, different scenarios that incorporate varied levels of water table management, together with the reported extent and classification of nutrient and drainage status of these lands, enable a broad range of GHG emissions to be estimated. If Ireland were to meet its target of reducing the management intensity of 80,000 ha of drained organic soil under grassland, emissions from these lands will potentially reduce by 590.44 kt CO₂-eq yr⁻¹. It may be difficult to fully rewet these lands, so other scenarios were also considered to demonstrate the potential emission reductions associated with raising the water table level from the currently assumed deeply drained status to shallow drained or a combination of both shallow drained and rewetted status. These scenarios provide a framework to explore different pathways to meet emission reduction targets for countries with significant extents of grassland on organic soils.

1. Introduction

Peat soils form in waterlogged environments where anaerobic conditions prevent the decomposition of organic material (Liu et al., 2023). Due to their storage of organic material, peatlands contain large amounts of carbon relative to their land cover area across the globe. These areas can be found in tropical, temperate and boreal climates, and may be defined regionally or locally based on how they were formed and how much organic material is present in the soil (Chen et al., 2024). Peat soils may be ombrotrophic, forming under the influence of precipitation, or minerotrophic, forming through the input of groundwater. In general, ombrotrophic peat soils are considered nutrient-poor and may be called blanket or raised bogs, whereas minerotrophic peat soils are considered nutrient-rich and may be called fens (Lourenco et al., 2023; Hammond, 1981).

Peat soils within the European Union (EU) account for approximately

only 5.6% of global peat soils (Tanneberger et al., 2017; UNEP, 2022), but 50% of these soils are drained (using deep open drainage channels and/or interlinked field drains) or degraded for a variety of reasons, including for agriculture, horticulture, forestry and peat extraction (Evans et al., 2021; Leifeld and Menichetti, 2018; UNEP, 2022). Where the drainage of peatlands occurs, these areas transform from carbon sinks to carbon emitters, mainly through the lowering of the water table which allows for oxygenation of the soil and decomposition of the stored organic material (Evans et al., 2021; Leifeld and Menichetti, 2018).

These areas are estimated nationally and reported in EU member states' GHG National Inventory Documents and National Inventory Reports as part of their annual GHG emission inventories; however, uncertainties about the extent of peat soils exist (Martin and Couwenberg, 2021; van Giersbergen et al., 2025). This is due to varying definitions of organic soils that can be used, since the Intergovernmental Panel on Climate Change (IPCC) definition does not specify minimum

* Corresponding author.

E-mail address: eve.daly@universityofgalway.ie (E. Daly).

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thickness of the organic layer and allows for country-specific soil definitions (Lourenco et al., 2023; Martin and Couwenberg, 2021). When considering organic soils within a country, it is important to know the country's definition of organic soils and when estimating emissions from organic soils to compare multiple countries, a standard definition must be applied to each country which may change organic soil extents and emission estimates from those reported in country-specific documents (UNEP, 2022; Martin and Couwenberg, 2021; van Giersbergen et al., 2025).

In this paper, we are interested in peat soils that have been converted to permanent grassland in areas of low elevation (< 300 m OD; Rodwell et al., 2007). For peat soils to be used for grassland, some degree of artificial drainage is used as the water table must be sufficiently low to allow for the cultivation of grass species (e.g., 40 cm below ground level) and for the soil to be stable for farm machinery and livestock access (Tiemeyer et al., 2024; Wilson et al., 2016). Emissions from drained peat soils are estimated using the area of these soils in a country and an emission factor that is based on Tier 1, 2 or 3 level data as defined by the IPCC (2006); (2014). These estimates are therefore only as precise as the accuracy of the estimate of extent of peat soils and the emission factor used. Based on the 2020 national GHG inventory submissions, which cover the period 1990–2018, EU member states estimated that they were emitting 43 Mt of carbon dioxide-equivalent (CO₂-eq) from grassland on organic soils. However, a study published in 2021 (Martin and Couwenberg, 2021) refined these estimates on a country-by-country basis by updating peat extent estimates for each EU member state using a standard definition of peat soil and refining emission factors where possible. This method estimated CO₂-eq emissions from grassland on peat soils in the EU to be 65 Mt (Martin and Couwenberg, 2021), highlighting the potential for variability and on-going uncertainty. Estimates of extent of grassland on peat soils and estimated emissions from these lands are updated by each EU member state every year for their annual GHG emission inventory submissions, as land use changes are implemented and further refinement of area estimates and emission factors are applied according to any updated information available at the time of reporting.

To reduce the amount of GHG emissions from peat soils that have been drained and converted to grassland, some countries in the EU have developed plans to reduce management intensity or actively raise the water table so that decomposition of organic material in the peat soils is slowed or stopped (Nordbeck and Hogl, 2024; Nordbeck et al., 2025). Rewetting peat soils that have been drained for use as grasslands is covered under several EU policies to work toward emissions reduction targets set out in the Paris Agreement (UNFCCC, 2015). Priority areas for peatland restoration are located in Ireland, Belgium, the Netherlands, Luxembourg, Germany, Poland, the Baltic States and Romania (van Giersbergen et al., 2025). Similarly, according to the Greifswald Mire Centre (2019), the largest peatland emitters of GHG in total in the EU are Germany, Finland, Poland, Ireland, Romania, Sweden, Latvia, Lithuania and the Netherlands. These management policies for grassland peat soils can represent a move toward restoration of these lands to their original peatland function or act as a mitigation tactic to reduce the amount of GHG emissions while enabling their continued use for livestock grazing or paludiculture to some degree (Ziegler et al., 2021). Efforts to manipulate the water table level in different types of drained peat soils have been studied in many countries over varying time periods (Bring et al., 2022; Kreyling et al., 2021; Menberu et al., 2016). Common methods to raise the water table level include open surface drain blocking, the construction of berms or pools, site reprofiling and re-establishment of peat-forming vegetation (Armstrong et al., 2009; Green et al., 2017; Holden et al., 2017).

Beginning in 2024, EU member states must include peatland policy strategies in their Common Agricultural Policies (CAP) (Nordbeck et al., 2025). Despite the guidance to include peatland strategy in CAP, it is difficult for countries to develop such plans when the extent of peatland and its drainage and nutrient status remain uncertain, and the emission

factors needed to calculate emissions are not based on country-specific information (Nordbeck et al., 2025). A comprehensive climate policy target for emissions reductions from drained peatlands was found to be lacking in both European and country-specific policies (Chen et al., 2023). Although there are targets to rewet a certain area of peatlands in countries where these lands contribute to LULUCF emissions estimates, it can be difficult to determine if targets are met when they are based on percentages of total drained peat area, but these total areas are not known in all countries (Martin and Couwenberg, 2021; Nordbeck and Hogl, 2024; Nordbeck et al., 2025). It is therefore essential for countries to accurately estimate the extent of drained organic soil under grassland management, as well as the drainage depth and nutrient status of these lands, to determine possible emissions from these lands and the potential effectiveness of mitigation measures such as rewetting and/or water table management.

Therefore, the objectives of this study are to: (1) assess the extent of grassland on organic soils across the EU and their associated GHG emissions; (2) use a systematic review process to quantify the potential effectiveness of efforts to raise the water table level on such lands; and (3) evaluate the potential impact of raising the water table level on GHG emissions from such lands using Ireland as a case study.

2. Materials and methods

2.1. Extent of grassland on organic soils across the EU and the GHG emissions from these lands

These data come largely from the study by Martin and Couwenberg (2021) using the GHG emissions reported by each of the EU member states in 2020 for the years 1990–2018. That study offers a direct comparison of emissions from EU member states at the time of its publication using a standard methodology. In this paper, the CO₂ and CH₄ emissions (kt CO₂-eq yr⁻¹) from organic soil under grassland reported by Martin and Couwenberg (2021) were summed for each EU country with a measurable amount of such lands. These emissions were then divided by the total reported country emissions (Martin and Couwenberg, 2021) to determine what percentage of total country emissions could be attributed to LULUCF emissions from organic soils under grassland for each EU country.

2.2. Systematic literature review: quantify the potential effectiveness of efforts to raise the water table on such lands

The systematic review process of available published papers followed a PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) approach (Page et al., 2021). This process used four steps to narrow down search results for published papers. The first step used a keyword search (*peat* OR bog OR fen OR "blanket bog" OR "raised bog" AND (rewet* OR "drain block" OR "drain blocking" OR "ditch block" OR "ditch blocking")*) within titles, abstracts, and keywords of published work on the Web of Science (WoS) and Scopus databases. This step returned 989 and 1194 results from each database, respectively. The second step included a new string of keywords, in addition to those used in the first step to further narrow down the results *AND (impact* OR effect* OR influenc* OR respons* OR chang*) AND ("water table" OR "water level") NEAR/15 (depth OR level* OR position* OR dynamics OR fluctuation* OR rise* OR rais* OR chang*)) AND (measur* OR monitor* OR observation* OR quantif* OR track* OR record* OR empirical* OR data)*, which returned 177 results from WoS and 195 results from Scopus. The third step further refined the results by limiting the language to English and the document type to articles and adding to the keyword string *AND (grassland* OR pasture* OR meadow* OR forage* OR graz* OR agricultur* OR "organic soil*")*. This step returned 59 results from WoS and 63 results from Scopus.

The fourth step was manually reviewing the title, abstract and the keywords to select the most relevant and appropriate articles regarding

the scope of this paper. During this step articles that focused on tropical peatlands or forested peatlands were eliminated, as were those that detailed modelling, remote sensing or ex-situ observations (e.g., mesocosms, monoliths, incubations). Finally, studies where the full text was inaccessible were also removed during this step. This step resulted in 21 relevant articles that provide an overview of the different rewetting techniques and the range of change in water level observed post-rewetting in peat soils that were drained for grassland use.

2.3. Scenario testing: what is the potential impact of raising the water table level in these lands on GHG emissions in Ireland?

2.3.1. Criteria for case selection: Ireland

Ireland was selected as a suitable country to use for the case study for several reasons. Ireland has a relatively large area of organic soil under grassland management and the emissions from these lands account for a relatively high proportion of total LULUCF emissions for the country (Table 1). Peat soils in Ireland are relatively well mapped (Connolly and Holden, 2009; Connolly, 2018; Creamer et al., 2014; Fealy and Green, 2009; Hammond, 1981; O'Leary et al., 2025) and country-specific data are available in some instances to allow for the use of Tier 2 emission factors (Aitova et al., 2023; EPA, 2026). Ireland is also targeting reducing the management intensity of organic soils under grassland management to reduce emissions from these lands (Government of Ireland, 2025).

2.3.2. Grassland on peat soils: National extent in Ireland

There are an estimated 338,920 ha of grassland on organic soils in Ireland (EPA, 2026). In Ireland, peat soils are defined as having greater than 20% organic carbon ($\approx 34\%$ organic matter content) and having an organic or peat layer thicker than 30 cm (Renou-Wilson et al., 2011). These soils are categorised as being either nutrient-poor or nutrient-rich based on estimates of extent of different peat soil types present in

Table 1

Area and total estimated emissions of organic soils that are being used for grassland in EU member states (adapted from Martin and Couwenberg, 2021). The percentage of estimated emissions from organic soils under grassland of the total country emissions from each member state is also reported (adapted from Martin and Couwenberg, 2021). Member states with no area of organic soils under grassland (Cyprus, Greece, Luxembourg, Malta, Portugal and Slovakia) have been omitted. Although reported in Martin and Couwenberg (2021), Great Britain has been omitted as it is no longer a member state of the EU.

EU member state	Estimated extent organic soil under grassland (kha)	Total estimated LULUCF emissions from organic soil under grassland (CO ₂ and CH ₄) (kt CO ₂ -eq yr ⁻¹)	% LULUCF emissions from organic soil under grassland of total country emissions
Austria	40.00	1022.40	1
Belgium	4.50	72.50	0
Bulgaria	6.88	110.85	0
Croatia	0.23	5.40	0
Czechia	4.25	101.57	0
Denmark	51.62	1233.53	2
Spain	13.00	310.68	0
Estonia	48.03	1147.85	5
Finland	66.91	999.68	2
France	58.62	1400.85	0
Germany	970.48	24,567.68	3
Hungary	5.00	119.49	0
Ireland	332.93	5286.80	9
Italy	2.07	49.42	0
Latvia	79.69	1904.44	14
Lithuania	68.60	1639.49	8
Netherlands	277.40	6629.49	3
Poland	761.69	18,203.26	5
Romania	5.04	120.35	0
Slovenia	1.09	26.14	0
Sweden	27.72	316.17	3

lowland agricultural settings. It is estimated that 55% of the total area (i. e., 186,406 ha) is nutrient-poor, being either remnant raised or blanket bog, and that the remaining 45% of the total area (152,514 ha) is nutrient-rich, and therefore considered fen peat soil (EPA, 2026; Hammond, 1981).

Approximately 141,000 ha of the 338,920-ha total, are considered 'improved' or drained grassland on peat soils (EPA, 2026). All of the estimated 141,000 ha of drained grassland in the national GHG emission inventory are considered deeply drained, since no information on drainage status of these lands is currently available (EPA, 2026). This is in line with IPCC guidance whereby if the drainage depth is not known, deep drained status should be applied (IPCC, 2014). The remaining estimated 197,920 ha of grassland on peat soils, which are not intensively managed, do not have active or maintained drainage systems (in-field or open surface drains) and are classified as 'rewetted organic soils under grassland' (EPA, 2026) for the purpose of assigning emission factors. These lands are in some form of rewetted status due to the lack of maintenance of drainage systems. However, they are distinct from the rewetting of organic soils as described by the IPCC (2014), which is a deliberate action of raising the water table level to near surface saturation (EPA, 2026). These lands which are classified as rewetted currently use the same emission factors as those deliberately rewetted (EPA, 2026; IPCC, 2014). The breakdown of grassland on organic soils in Ireland by nutrient and drainage status as reported in Ireland's national GHG emission inventory is shown in Table 2.

2.3.3. Scenario development

Three scenarios illustrating possible emissions reductions due to water table management in areas of grassland on organic soils in Ireland were developed. The area of grassland on organic soils in Ireland (Table 2) and the emission factors used by the EPA (2026) (Table 3), were used to estimate emissions from these lands, which were then applied to the scenarios.

The national GHG emission inventory utilises a mix of Tier 1 and Tier 2 emission factors to estimate emissions from each of the categories of grassland organic soil as shown in Table 3 (EPA, 2026). For the emission factors to be used in emissions estimate comparisons, all emission factors were converted to t CO₂-eq using the AR5 CO₂ global warming potential (GWP₁₀₀) values (Figure S1). Because N₂O is reported in the Agriculture sector in Ireland's GHG emission inventory and contributes a small amount to total emissions from these lands, it was omitted from the calculation of total emissions for the scenarios presented, which only include emissions from the LULUCF sector (see Figure S2 for emissions estimates from the scenarios that include N₂O).

Ireland is targeting implementing 'reduced management intensity' on 80,000 ha of drained organic soil by 2030 (Government of Ireland, 2025) to reduce emissions from the LULUCF sector. Reduced management intensity may refer to changing drainage status from deep to shallow, not cleaning drains in order to slow water through the natural accumulation of sediment and debris in drains, implementing active water table management to raise the water table level to within 10 cm of the ground level (rewetting, per IPCC, 2014), and other activities such as reducing fertiliser application or livestock stocking rate (Government of Ireland, 2025). There is therefore a range of options to meet this target

Table 2

Estimates of current grassland extents based on nutrient and drainage status in Ireland.

Drainage status	Area (ha)	Nutrient status	Drainage status	Area (ha)
Drained	141,000	Poor	Shallow	–
			Deep	77,550
		Rich	Shallow	–
Rewetted	197,920	Poor	Deep	63,450
			NA	108,856
		Rich	NA	89,064

Table 3

Emission factors (and 95% confidence interval) used by the EPA (2026) in Ireland to estimate emissions from the categories of grassland peat soils as defined in the National Inventory Document (2026). Abbreviations used: DOC=dissolved organic carbon, LULUCF=Land Use, Land Use Change and Forestry.

Grassland type	CO ₂ on-site emission factor	Offsite ^a DOC emission factor	CH ₄ soil emission factor	CH ₄ ditch emission factor	N ₂ O emission factor
	LULUCF				Agriculture^b
Nutrient-poor, shallow drained ^c	1.3 (0.04 – 2.55) t CO ₂ -C ha ⁻¹ yr ⁻¹ (Tier 2)	0.31 (0.19 – 0.46) t C ha ⁻¹ yr ⁻¹ (Tier 1)	11.76 (3.51 – 20.03) kg CH ₄ ha ⁻¹ yr ⁻¹ (95% of area) (Tier 2)	527 (285 – 769) kg CH ₄ ha ⁻¹ yr ⁻¹ (5% of area) (Tier 1)	4.3 (1.9 – 6.8) kg N ₂ O-N ha ⁻¹ yr ⁻¹ (Tier 1)
Nutrient-poor, deep drained ^d	1.3 (0.04 – 2.55) t CO ₂ -C ha ⁻¹ yr ⁻¹ (Tier 2)	0.31 (0.19 – 0.46) t C ha ⁻¹ yr ⁻¹ (Tier 1)	11.76 (3.51 – 20.03) kg CH ₄ ha ⁻¹ yr ⁻¹ (95% of area) (Tier 2)	1165 (335 – 1995) kg CH ₄ ha ⁻¹ yr ⁻¹ (5% of area) (Tier 1)	4.3 (1.9 – 6.8) kg N ₂ O-N ha ⁻¹ yr ⁻¹ (Tier 1)
Nutrient-rich, shallow drained ^c	3.6 (1.8 – 5.4) t CO ₂ -C ha ⁻¹ yr ⁻¹ (Tier 1)	0.31 (0.19 – 0.46) t C ha ⁻¹ yr ⁻¹ (Tier 1)	39 (-2.9 – 81) kg CH ₄ ha ⁻¹ yr ⁻¹ (95% of area) (Tier 1)	527 (285 – 769) kg CH ₄ ha ⁻¹ yr ⁻¹ (5% of area) (Tier 1)	1.6 (0.56 – 2.7) kg N ₂ O-N ha ⁻¹ yr ⁻¹ (Tier 1)
Nutrient-rich, deep drained ^d	6.1 (5 – 7.3) t CO ₂ -C ha ⁻¹ yr ⁻¹ (Tier 1)	0.31 (0.19 – 0.46) t C ha ⁻¹ yr ⁻¹ (Tier 1)	16 (2.4 – 29) kg CH ₄ ha ⁻¹ yr ⁻¹ (95% of area) (Tier 1)	1165 (335 – 1995) kg CH ₄ ha ⁻¹ yr ⁻¹ (5% of area) (Tier 1)	8.2 (4.9 – 11) kg N ₂ O-N ha ⁻¹ yr ⁻¹ (Tier 1)
Nutrient-poor, rewetted ^e	0.85 (-1.6 – 3.3) t CO ₂ -C ha ⁻¹ yr ⁻¹ (Tier 2)	0.24 (0.14 – 0.36) t C ha ⁻¹ yr ⁻¹ (Tier 1)	68.1 (20.9 – 115.2) kg CH ₄ -C ha ⁻¹ yr ⁻¹ (100% of area) (Tier 2)	N/A	N/A
Nutrient-rich, rewetted ^e	0.5 (-0.7 – 1.7) t CO ₂ -C ha ⁻¹ yr ⁻¹ (Tier 1)	0.24 (0.14 – 0.36) t C ha ⁻¹ yr ⁻¹ (Tier 1)	216 (0 – 856) kg CH ₄ -C ha ⁻¹ yr ⁻¹ (100% of area) (Tier 1)	N/A	N/A

^a Offsite emissions are those released through the drainage of water from the site (IPCC, 2014)

^b Nitrous oxide (N₂O) emissions are reported under the Agriculture sector in the GHG emission inventory. This sector is where emissions from enteric fermentation, manure management, agricultural soils, liming and urea application are reported.

^c Shallow drained soils are those with average annual water table levels above 30 cm (IPCC, 2014)

^d Deep drained soils are those with average annual water table levels below 30 cm (IPCC, 2014)

^e Rewetting is defined as ‘the deliberate action of raising the water table on drained soils to re-establish water saturated conditions’ (IPCC, 2014)

by 2030 including rewetting the full 80,000 ha, or some portion of it, or by changing the full 80,000 ha, or some portion of it, from deeply drained to shallow drained. The scenarios outlined below attempt to show potential emission reductions based on the implementation of some of these options.

The three scenarios developed are called the ‘rewet scenario’, ‘the shallow drained scenario’ and the ‘mixed scenario’. Each uses a 55% nutrient-poor / 45% nutrient-rich split to match what is used in the national inventory document (EPA, 2026; Hyde, Bernard, personal communication, 2026).

Scenario 1: The rewet scenario assumes that a certain amount of land will be converted from deeply drained organic soils under grassland to rewetted organic soils under grassland as per the definition of the EPA (2026). For this scenario, areas of 20,000 ha, 40,000 ha, 60,000 ha, 80,000 ha and 141,000 ha were assumed to move from deeply drained (>30 cm; IPCC, 2014) to rewet status (water table level near surface; IPCC, 2014) through active raising of the water table to assess the impact on emission reductions. For this scenario, the 55% nutrient-poor / 45% nutrient-rich breakdown of drained grassland on organic soil was applied to the land being rewet.

Scenario 2: The ‘shallow drained scenario’ considered the emissions reductions if the same 80,000 ha of deeply drained land targeted for reduced management intensity had the water table level raised to fall within the shallow drainage category (< 30 cm; IPCC, 2014) rather than fully rewetted. For this scenario, the same iterations of 20,000 ha, 40,000 ha, 60,000 ha, 80,000 ha and 141,000 ha were used to determine the emissions reductions if each of these amounts of deeply drained lands (> 30 cm; IPCC, 2014) became shallow drained. Here, the 55% nutrient-poor / 45% nutrient-rich ratio of drained grassland on organic soil was applied to the land being changed from deeply drained to shallow drained. For this scenario, no additional lands are rewetted so the extent of rewetted grassland on organic soils remains the same as the current estimate (197,920 ha) in each iteration.

Scenario 3: The ‘mixed scenario’ used the iterations of 20,000 ha, 40,000 ha, 60,000 ha, 80,000 ha and 141,000 ha to determine the emissions reductions if half of each of these amounts of lands were rewetted and the remaining half became shallow drained rather than deep drained (for example, in the 60,000-ha scenario, 30,000 ha becomes rewetted and 30,000 ha becomes shallow drained). Here, the 55% nutrient-poor / 45% nutrient-rich breakdown of drained grassland on organic soil was applied to the land being changed from deeply drained to rewetted and shallow drained.

2.3.4. Uncertainty analysis

To assess the uncertainty associated with the scenarios, the ranges of the scenario inputs were determined and applied Monte Carlo analyses to compute the mean, standard deviation and 95% uncertainty interval for each area change iteration of each scenario. For the Monte Carlo analyses, 10,000 simulations for each iteration of each scenario were run. The parameters that were changed for the Monte Carlo analyses were the emission factors associated with each land use type and the percentage of nutrient-poor and nutrient-rich soil.

The emission factor ranges used for each are listed in Table 3. The upper and lower bounds of the 95% confidence interval for each LULUCF emission factor were converted to t CO₂-eq ha⁻¹ yr⁻¹ and summed to determine the upper and lower limits of the range for each land use type. The actual percentages of nutrient-poor and nutrient-rich grassland soils in Ireland are not well understood (Gilet et al., 2024). Although a 50% / 50% split may seem like a reasonable estimate (Paul et al., 2018), it may be that there is slightly more nutrient-poor soil (Aitova et al., 2023; Gilet et al., 2024) or slightly more nutrient-rich soil, since many nutrient-rich fens have been drained for grassland production (Foss, 2007; Hammond, 1981). To account for this range of possibilities, ranges of 45–55% were applied for both nutrient-poor and nutrient-rich soils in the Monte Carlo analyses.

3. Results and discussion

3.1. Extent of grassland on organic soils across the EU and the GHG emissions from these lands

It is estimated that 9–35% of European peat soils have been converted to grassland using artificial drainage, particularly in Germany, the Netherlands and Ireland (Offermanns et al., 2023). Within the EU countries, in 2018, 2.8 million ha of organic soils were estimated to be under grassland management, and these soils are estimated to emit 43–65 million tonnes of carbon dioxide equivalent ($\text{Mt CO}_2\text{-eq yr}^{-1}$) (Martin and Couwenberg, 2021).

Extents and estimated emissions of grassland under organic soils in the EU are shown by country in Table 1 (Martin and Couwenberg, 2021). This shows which countries have the most potential for emission reductions through the rewetting of organic soils under grasslands based on which countries have the largest extents of these areas and emissions from them. The reported total emissions from these lands are highest in Germany, Poland, the Netherlands and Ireland, which are also the countries with the largest area of organic soil under grassland. The countries where the emissions from organic soils being used for grassland represent the largest percentage of total country emissions are Ireland, Latvia and Lithuania.

It is important to note that these estimates were made in 2021 (Martin and Couwenberg, 2021) covering the 1990–2018 emission inventory submissions and therefore may already be outdated. For example, in Ireland, following the publication of several new studies, the EPA adjusted the area of drained organic soil under grassland management for the 2024 national emission inventory submission (EPA, 2024) which drastically changed emission estimates, but this change is not reflected in the estimates made by Martin and Couwenberg (2021) and summarised in Table 1. The analysis done by Martin and Couwenberg (2021) to standardise organic soil definitions across countries and update extents and emissions to compare multiple countries remains one of the only such studies completed. van Giersbergen et al. (2025) refined and updated GHG emission estimates from drained peatlands in the EU, but categories in that study combined grassland and cropland which makes it difficult to analyse how their methods impact the grassland category alone.

Using Ireland as a case study illustrates the importance of having an accurate estimate of the extent of drained organic soil under grassland for emissions estimates. The total extent of organic soil under grassland was similar in the national GHG emission inventory (EPA, 2026) to the estimate in Martin and Couwenberg (2021) (338,920 ha and 332,930 ha). Martin and Couwenberg (2021) assumed the entire extent of organic soil under grassland was deeply drained, as was reported in the 2020 Irish national GHG emission inventory (EPA, 2020). In the updated figures used in more recent national GHG emission inventory submissions, only 141,000 ha of organic soil under grassland was classified as deeply drained and the rest was considered functionally rewetted to some extent (Tuohy et al., 2023; EPA, 2026). This reduced the emission estimates of Martin and Couwenberg (2021) from 5286 kt $\text{CO}_2\text{-eq}$ (Table 1) to 3900 kt $\text{CO}_2\text{-eq}$ based on the land areas provided in 2026 national GHG emission inventory submission (EPA, 2026).

In van Giersbergen et al. (2025), the emission estimates were achieved by updating the area of organic soil under different land uses in EU countries to map hotspots of GHG emissions from drained organic soils. van Giersbergen et al. (2025) report estimated emissions for Ireland from grassland and cropland on organic soil as 11,630 kt $\text{CO}_2\text{-eq}$, which it compares to Ireland's 2023 national GHG emission inventory submission (8954 kt $\text{CO}_2\text{-eq}$; EPA, 2023) and Martin & Couwenberg's updated estimate (5892 kt $\text{CO}_2\text{-eq}$; 2021). This increase in emissions for Ireland reported by van Giersbergen et al. (2025) is due to their use of the 2023 national GHG inventory submission, which considered all organic soil under grassland as deeply drained; increased estimates of the amount of cropland on organic soils in Ireland; and the use of an

updated peat extent map of Ireland, which increased the area of organic soil under grassland to 423,000 ha (Gilet et al., 2024). However, this updated Irish peat soils map used a different basemap and a different definition of organic soils as it included shallow peat soils (>10 cm) in the mapping criteria (Gilet et al., 2024) and therefore expanded the extent of organic soils under grassland management in Ireland.

These updated estimated total emissions (Martin and Couwenberg, 2021; van Giersbergen et al., 2025) show the importance of accurately estimating the extent of these lands, as well as their land use and drainage status, since it is possible to get very different emission estimates based on these inputs. To accurately estimate emissions from these lands, other nations will need to accurately map areas of peat and the land use on peat soils, since different emission factors are applied to different land use categories. As shown by the example of Ireland, it can be difficult to accurately estimate the area of peat soil under grassland in a country and the emissions from these lands.

3.2. Quantify the potential effectiveness of efforts to raise the water table on such lands

Drain blocking and cessation of drainage/drain maintenance have been common rewetting techniques used by several studies on peat soil under grassland, which resulted in measurable water table rises (Görn and Fischer, 2015; Graf et al., 2022; Renou-Wilson et al., 2016; Rodríguez et al., 2025; Schrier-Uijl et al., 2014; Tong et al., 2026). Other techniques that have been used are subsurface irrigation, which resulted in water level rises (Best and Jacobs, 1997; Heller et al., 2025), and subsurface infiltration systems, which resulted in higher and more stable water table levels during dry periods (Harpenslager et al., 2024). In coastal and low-lying peatlands that would have been inundated by nearby surface water and were reclaimed using water pumping and dikes, studies found that dike removal and cessation of pumping resulted in water table rises (Koch et al., 2017; Minke et al., 2016; Schulz et al., 2011; Schwieger et al., 2022; Timmermann et al., 2006). Other studies reported on the impact of restricting outflow from sub-surface drainage (Lång et al., 2024; Kekkonen et al., 2025), pumping water into the field (Bockermann et al., 2024) and creating basins for paludiculture experiments (Vroom et al., 2024). A study on an Arctic grassland found that maintaining the water table between 25–50 cm below the ground surface reduced CO_2 emissions without significant CH_4 and N_2O emissions (Zhao et al., 2025).

The largest water table rises, those higher than 50 cm and sometimes over 100 cm, were seen at sites that were inundated by nearby surface water, particularly sites near seas where dikes were removed and flooding was allowed to occur (Koch et al., 2017; Schulz et al., 2011; Timmermann et al., 2006). Water table rises of between 20 and 40 cm were reported for subsurface irrigation (Best and Jacobs, 1997), controlled automatic pumping (Bockermann et al., 2024), drainage cessation (Görn and Fischer, 2015), drain blocking and filling with sawdust (Graf et al., 2022), controlling sub-surface drainage water outflow (Lång et al., 2024), maintaining a ditch water level of approximately 10 cm below the land surface (Schrier-Uijl et al., 2014) and unspecified rewetting activities (Schwieger et al., 2022 on percolation fens; Hoffmann et al., 2016). Heller et al. (2025) reported that subsurface irrigation resulted in a 13 cm water table rise and Renou-Wilson et al. (2016) observed an 18 cm average median annual water table rise after drain blocking due to lack of maintenance on nutrient-poor peat soil used for permanent grassland. Other studies reported smaller water table rises. Tong et al. (2026) found that discontinuation of drain maintenance at one site and the installation of clay dams at another resulted in a mean annual water table level that was ~ 7 cm higher than the control site. O'Leary et al. (2026), completed about one year after drain blocking, found no measurable impact of a drain block on the water table level and Heller et al. (2025) reported a 1 cm difference between the control site and drain blocking site four years after blocking.

These studies show the variation in water table responses that were seen after drain blocking and other rewetting techniques were used on peat soils drained for grassland. An important consideration was whether the goal of the water table management was to ‘restore’ the site and bring the water table level back to pre-drainage levels, implement paludiculture at the site, or if the water level changes occurred due to a lack of maintenance or other drainage activities. Due to the limited number of studies that address water table management on peat soils drained for permanent grassland, it is difficult to quantify the impacts of management techniques on these lands specifically. Some of the included studies were sub-field scale experiments involving water control and manipulation techniques that likely would not be feasible at the field scale or larger. Results from drain blocking through cessation of drain maintenance, damming or a combination of these techniques on grassland peat soils indicate that the effectiveness may be hard to predict with studies reporting water level changes ranging from greater than 20 cm (Graf et al., 2022) to no measurable impact (O’Leary et al., 2026). These results indicate that while changing the water table level may be possible at these sites, there have not been enough studies to accurately estimate what techniques will result in what level of water table change.

Countries that have coastal or riparian peatlands that have been reclaimed using dikes and dewatering pumping, such as Germany, the Netherlands and Denmark, may be able to return these areas to their pre-drainage level of inundation through the removal of dikes. Other countries where sub-surface drainage is common may find that controlling the outflow from these systems effectively raises the water table level on these lands. Countries that plan to rely solely on drain blocking through damming or by stopping drain maintenance will likely see varied results, depending on the effectiveness of the drainage system and the site characteristics.

3.3. What is the potential impact of raising the water table level in these lands on GHG emissions in Ireland?

Emissions from grassland on organic soils in Ireland (338,920 ha, Table 2; EPA, 2026) were estimated using the three developed scenarios and are presented in Fig. 1. The results can be summarised as follows:

Scenario 1 outcomes: The rewet scenario indicates that emissions will be lowered with a potential reduction in emissions of 590.44 kt CO₂-eq yr⁻¹ (or 15.1% of current emissions) if 80,000 ha of drained organic soils under grassland are rewetted. If all 141,000 ha of the

estimated deeply drained improved grassland on organic soils are rewetted, the potential reduction in emissions is 1040.65 kt CO₂-eq yr⁻¹ (or 26.7% of current emissions).

Scenario 2 outcomes: The shallow drained scenario indicates that emissions will be lowered with a potential reduction in emissions of 379.36 kt CO₂-eq yr⁻¹ (or 9.7% of current emissions) if 80,000 ha of the estimated deeply drained organic soils under grassland had their average annual water table levels raised to above 30 cm below the ground surface (shallow drainage). If all 141,000 ha of the estimated deeply drained improved grassland on organic soils have their average annual water table levels raised to shallow drainage status, the potential reduction in emissions is 668.62 kt CO₂-eq yr⁻¹ (or 17.1% of current emissions).

Scenario 3 outcomes: The mixed scenario indicates that emissions will be lowered with a potential reduction in emissions of 484.90 kt CO₂-eq yr⁻¹ (or 12.4% of current emissions) if 40,000 ha of deeply drained organic soils under grassland were rewetted and 40,000 ha of deeply drained organic soils under grassland had the average annual water table level raised to a shallow drainage level. If all the estimated 141,000 ha of deeply drained organic soils under grassland were evenly converted to rewetted or shallow drained (i.e., 70,500 ha allocated to each), the potential reduction in emissions is 854.64 kt CO₂-eq yr⁻¹ (or 21.9% of current emissions).

These scenarios indicate emission reductions are possible by raising the water table on deeply drained, organic grassland soils. Although the highest potential emissions reductions can be seen when the full extent of deeply drained organic grassland soils is rewetted, reductions are possible under each iteration of each scenario. The emissions reduction seen by rewetting 80,000 ha of deeply drained organic grassland soils could be achieved by converting at least 97,000 ha to the mixed scenario (48,500 ha shallow drained and 48,500 ha rewetted). If at least 125,000 ha of deeply drained organic grassland soils were changed to shallow drainage, the emissions reduction would be similar to that seen if 80,000 ha of deeply drained organic grassland soils were rewetted.

3.3.1. Uncertainty analysis

The scenarios presented in Fig. 1 indicate a reasonable estimate of emissions and emission reductions based on the best currently available input parameter data for Ireland (EPA, 2026). They are presented to explore how emission estimates may change due to land use change from deep drainage to shallow drainage and/or rewetted status using the

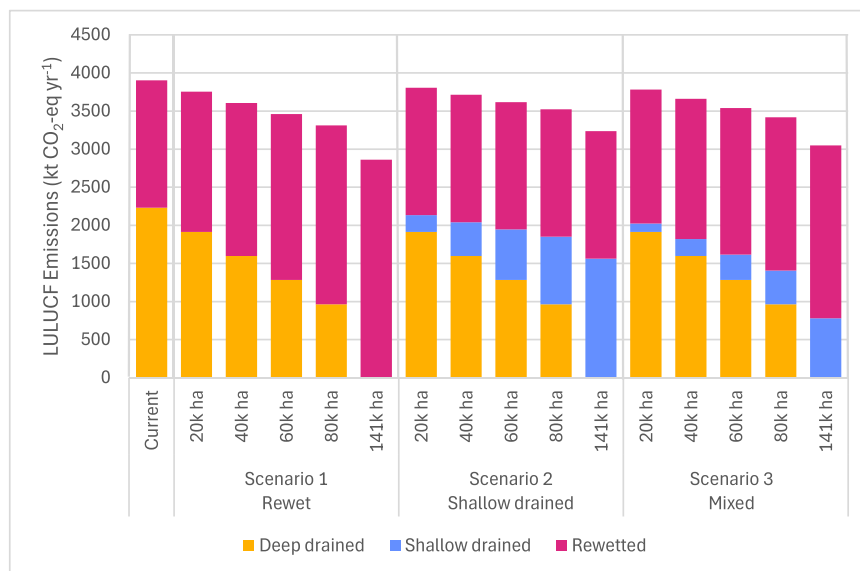


Fig. 1. Scenario 1–3 results showing how total estimated emissions would change from the current situation if scenarios 1–3 were applied to 20,000 ha, 40,000 ha, 60,000 ha, 80,000 ha and 141,000 ha of currently assumed deeply drained organic soils under grassland.

current methodology of Ireland's national inventory reporting. These numbers, however, should not be taken as absolute values as they depend on the accuracy of each input in each scenario and there is uncertainty associated with each input, as well as with the premise that we can feasibly control the depth of the water table in these lands.

There are numerous sources of uncertainty associated with the scenario analysis presented above. The Monte Carlo simulations showed a wide range of emissions for each iteration of each scenario and, due to the higher percentage of nutrient-rich soil used in the simulations, higher mean values were obtained in each scenario iteration than those reported in Fig. 1 (Table S1). In the rewet and mixed scenarios, introducing more rewetted and more nutrient-rich soil into the simulations caused more uncertainty, evidenced by a wider range of high standard deviations and larger 95% uncertainty ranges (Table S1). This is due to higher uncertainty ranges for the emission factors used for the rewetted land use types, particularly the nutrient-rich soil, compared to the shallow drained land use types. The rewetted nutrient-rich grassland emission factor (Tier 1) has an uncertainty range of $-2.05 - 39.51 \text{ t CO}_2\text{-eq ha}^{-1} \text{ yr}^{-1}$, with the large upper bound of uncertainty being due to potentially large emissions from soil CH_4 . It is well documented that there is a CH_4 spike of unknown duration following rewetting of peat soils (Evans et al., 2021; Kalhori et al., 2024; Kjær et al., 2025). Despite the large uncertainty associated with emission estimation, the means of each of the Monte Carlo simulations indicated an emissions reduction when compared to the mean of the Monte Carlo simulations for the current emissions scenario (Table S1).

It is now known that it may not be easy, or even possible, to raise the water table level to rewetted status across these lands both due to limitations in the water storage capacity of these soils and due to the need for continued use as grassland sites for agriculture (O'Leary et al., 2026; Pierce et al., 2025; Tuohy et al., 2023). Sites with very deep ($< 60 \text{ cm}$) average annual water table depths and relatively shallow organic soil layers exist within the improved grassland on organic soils classification and it may be particularly difficult to raise the water table level at these sites due to their reduced water storage capacity (Pierce et al., 2025). Intentionally blocking artificial drainage structures in these lands is an engineering option that may result in the raising of the water table level to rewetted or shallow drained status; however, the effectiveness of this at the field or landscape scale requires more research, as the impact of drain blocking may be limited (Heller et al., 2025; O'Leary et al., 2026). Additional engineering solutions, such as subsurface irrigation, may be needed to raise the water table level on these lands (Heller et al., 2025). Because of the difficulty and cost associated with fully rewetting deeply drained grassland on organic soils through engineered interventions, the 'shallow drained' and 'mixed' scenarios are presented to illustrate the potential for emissions reductions by raising the water table level to an average of $< 30 \text{ cm}$ below the ground surface (shallow drained scenario) or using a combination of rewetting and shallow drainage (mixed scenario). These scenarios show smaller reductions in potential emissions compared to the rewet scenario but still show reduced emissions and may allow for continued use of these lands as grassland when a shallow drainage status is maintained. Shallow drainage of these lands may also limit the increase in CH_4 emissions associated with the rewetting of drained peat soils (Evans et al., 2021). In areas of improved grassland on organic soils where productive land will be rewetted, paludiculture is an option for continuing economic productivity while also reducing GHG emissions (Bockermann et al., 2024).

The 141,000 ha of improved grassland on organic soil are considered deeply drained (EPA, 2026), due to a lack of site-specific information about the drainage status of these lands per IPCC guidance (2014). Determining the actual drainage status of areas of grassland on organic soils will improve the estimate of emissions from these lands. Some of these lands that are considered deeply drained may be shallow drained (Pierce et al., 2025) and emission estimates from these lands may be different than currently estimated. Pierce et al. (2025) found that grassland sites with deep drainage ditches on raised bog peat soils may

not be effectively drained by existing artificial drainage infrastructure due to high water storage capacity and may be shallow drained. Drain functionality changes over time and since new large-scale drainage schemes in Ireland are no longer being undertaken by the Office of Public Works (Arterial Drainage Amendment Act, 1995), more lands that are currently deeply drained and are not being re-drained or maintained may be reverting slowly or have already reverted to rewetted or shallow drained status (Tuohy et al., 2023). Mapping peat soil types under grassland accurately may be useful as a proxy to estimate drainage status of lands without needing to monitor water table levels, however more studies should be completed to assess the relationship between peat soil type and drainage status.

The Irish case study illustrates how much of current emission estimates from these lands rely on accurate estimates of input data. In addition to the extent of drained organic soils under grassland and the drainage status of these lands, the nutrient status of these lands is also estimated. Since emission factors for nutrient-rich and nutrient-poor organic soils under grassland differ, more accurately mapping nutrient-rich and nutrient-poor organic soils under grassland management would improve estimates of emissions from these lands. The largest emissions reductions can be gained by targeting nutrient-rich soils that are deeply drained and raising the water table level to be either shallow drained or rewetted (Table 3; Figure S1). Although Ireland has moved from using generic Tier 1 emission factor to adopting country-specific Tier 2 emission factors where possible, there does not yet exist enough country-specific data to utilise Tier 2 emission factors for all categories of organic soil under grassland in Ireland (Table 3; Aitova et al., 2023). Additional research on GHG emissions from grassland sites in Ireland would improve these emission factors and further refine emissions estimates from organic soil under grassland in Ireland.

Ireland is an example of an EU country with a large percentage of peat soil present and where there is a significant amount of that organic soil under grassland management meaning there are opportunities to reduce emissions from these lands through using water table management. The scenarios presented (Fig. 1) and the uncertainty associated with them emphasise the importance of accurately estimating the total peat area under grassland management, the drainage and nutrient status of these lands, and the potential change in drainage status that may result from water table management in order to determine the potential emission reductions from management interventions. Additionally, refining emission factors from Tier 1 to Tiers 2 or 3 will enable countries to better estimate their emissions from these lands and better estimate potential emission reductions. The Irish scenarios case study can be replicated for other countries that are targeting emission reductions through water table management, but the accuracy of these estimates will depend on the accuracy of the inputs available for each country, and scenario testing should be repeated as new data on the input parameters become available.

4. Conclusion

Accurate estimates of emissions from organic soils under grassland are crucial for countries that have significant areas of such lands and that are seeking to reduce emissions from their LULUCF sector. However, it is difficult for these countries to accurately estimate their emissions from these lands when extents of these lands and their drainage and nutrient statuses are not fully understood, and when there is a lack of country-specific emission factors. Based on current estimates of extents and emissions from organic soils under grassland in the EU, these lands are being targeted by policies for active water table management, reduced management intensity, rewetting, restoration, or some combination of these practices. Although there exist many studies on these practices in peat soils, their application to peat soils that have been converted to permanent grassland remains uncertain due to a lack of grassland-specific studies.

It may not be possible or practical to use engineering solutions to raise the water table level to rewetted status in these lands, especially when large areas of them are targeted for this management practice change. Conversely, some of these lands may naturally return to a shallow water table level if artificial drainage systems are not maintained. If these areas are to be targeted for management changes to meet emissions reductions targets, further study and understanding of their characteristics and behaviour is needed. This study presents several iterations of three scenarios that show the potential emission reductions in Ireland if some or all the currently estimated deeply drained grassland on organic soil is changed to shallow drained or rewetted. The scenarios presented in this study for Ireland illustrate the need for accurate estimates of input data for emissions estimates and the potential difficulties faced in implementing these policies on the ground. These scenarios also provide an exploratory framework to assess different ways that emission reduction targets may be met through the management of agricultural land drainage.

CRedit authorship contribution statement

Hilary Pierce: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Owen Fenton:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Eve Daly:** Writing – review & editing, Supervision, Funding acquisition. **Mark G. Healy:** Writing – review & editing, Supervision, Funding acquisition. **Patrick Tuohy:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.envsci.2026.104495](https://doi.org/10.1016/j.envsci.2026.104495).

Data availability

Data will be made available on request.

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