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Review

Drainage status of grassland peat soils in Ireland: Extent, efficacy and implications for GHG emissions and rewetting efforts

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ABSTRACT

Peatlands have been artificially drained and degraded over 100s of years and have released huge amounts of carbon dioxide (CO_2) as a result. In organic grassland soils, raising the water table to prevent such emissions is being proposed to meet national greenhouse gas emission targets for the land use sector. At present, all of these soils (335,000 ha) are assumed to be drained (as no information has been available on their drainage status) within national emission inventory reporting and are therefore responsible for significant emissions (8–9 million tonnes CO_2-equivalent annually). The objective of the present study was to collate studies relating to the drainage status of peat soils in Ireland to present alternative scenarios with regard to actual drainage status of organic soils and their estimated emissions. From a drainage design perspective, evidence suggests that relatively small proportions of the grassland peat area was drained effectively using optimal in-field drain spacings required to control the water table at 0.4–0.5 m. Open drains excavated on such soils have limited capacity to laterally control the water table depth beyond short distances. Furthermore, the lack of long-term routine maintenance post installation ensures the redundancy of many drainage systems over time. New drainage installations are therefore likely replacing existing infrastructure and not necessarily increasing the drained area at any given time. This evidence supports literature from the 1980s which state that relatively low proportions of the grassland peat area has been subjected to effective drainage. Scenario testing results showed that likely emissions from the most probable scenario (with total area drained equating to 90,000–120,000 ha) are 3.6–4.7 million tonnes CO_2-equivalent, approximately 40–53% of current national emission inventory estimates. The incorporation of such a refinement into the national inventory could offer a significant reduction in estimated GHG emissions from the grassland land use sector in national emission inventory reporting.

1. Introduction

Peatlands form where high rainfall or impeded drainage causes waterlogging, restricting oxygen supply and suppressing decomposition of organic matter (Evans et al., 2021). Peat is the accumulation of partially decomposed organic material, which under suitable conditions can form extensive deposits over wide areas, known as bogs. Complete decomposition of organic material is inhibited by low oxygen levels, induced by waterlogging, while high acidity also plays a role, as low pH conditions will repress decomposition (Murayama and Bakar, 1996; Huat et al., 2011; Yli-Halla et al., 2022). In their natural state bogs facilitate a rich diversity of plant life and act as a habitat for numerous species of international importance (Renou-Wilson et al., 2018). Furthermore, given the accumulation of vast amounts of organic material, peatlands offer significant value in terms of carbon (C) storage (Joosten et al., 2012; Turner et al., 2013). Peatlands cover only 3% of the Earth's land surface but store about 15–30% of the world's soil C as peat (Limpens et al., 2008; Liu et al., 2020a). In Ireland, peat soils cover approximately 1.46 million ha or 21% of the land surface and store approximately 2.3 billion tonnes of C (Wilson, 2021). In Europe, only Finland, Estonia and Scotland can boast comparable proportions of peat soil land cover (Tanneberger and Belous, 2017).

Over many generations, drainage of large swathes of these peats reduced flooding and enabled trafficking to allow cutting operations for fuel and pasture enterprises for agriculture to thrive (Bruton and Convery, 1982; Mc Afee, 1984; Eaton et al., 2008), both of which

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removed C from these soils. Such practices were actively encouraged and incentivised with a focus on maximising the peat resource in terms of energy production, horticulture and agriculture (Hammond, 1981; Finn et al., 1984). The intensification of the agricultural use of peatlands over time has been documented elsewhere; in Poland (Łachacz et al., 2023), the United Kingdom (Dawson et al., 2010) and Germany (Krüger et al., 2015). In Ireland, peatlands have been drained and degraded over 100s of years (Common, 1970; Wilcock, 1979; Carroll-Burke, 2002) for afforestation, turf cutting for domestic fuel, peat extraction for energy, agriculture, and horticulture (NPWS, 2015) and these areas have released significant GHG emissions.

The depth of the water table within the peat is the key factor, which controls whether accumulation or decomposition is the dominant process. Consequently, the long term stability of peat is very sensitive to any changes in hydrology brought about by drainage (Holden et al., 2004; Worrall et al., 2007). As the water table depth is increased, greater aeration close to the surface increases decomposition in the unsaturated zone, affecting fundamental changes in the composition and characteristics of the peat profile (Krause et al., 2021; Tanneberger et al., 2021). When effectively drained, aerobic conditions mineralise C stored in the peat and greenhouse gases (GHG) such as carbon dioxide and nitrous oxide are released to the atmosphere (Bubier et al., 2003; Liu et al., 2020b; Ma et al., 2022). This process transforms peatlands from C-sinks into C-sources (Leifeld and Menichetti, 2018; Regan et al., 2019) which are estimated to have contributed approximately 6% of anthropogenic CO_2 emissions to date (Joosten et al., 2012). It was estimated by Leifeld et al. (2019) that by 2015, drained peatlands had already emitted about 80 billion tonnes of CO_2 globally - and that this cumulative amount would approximately triple by 2100. Substantial cuts in GHG emissions are required in line with international agreements to reduce climate change and its impacts. The land use sector therefore needs targeted changes in management such that C sources are minimised and sinks promoted on a local and global scale. Therefore, C rich peatlands are of particular importance in this context and targets to ensure their contribution towards a net zero emission future are needed.

The Irish State was involved in field drainage from the 1940's to the 1980's, when grant support was available for this purpose (Bruton and Convery, 1982; Burdon, 1986). The Land Rehabilitation Project, from 1949, provided state aid for drainage work on farms and throughout the project circa 1.2 million hectares of land, across all soil types, were affected (Galvin, 1966; Burdon, 1986; Ryan, 1986). Prior to this, a number of arterial drainage works (Arterial Drainage Act, 1945) incorporating most main river catchments and important tributaries facilitated efficient drainage of the farmland in their catchments. This work commenced in 1842 under the control of the Office of Public Works. The total area drained under the various schemes, both arterial and field drainage, is approximately two million hectares, accounting for nearly 30% of the total land area (Burdon, 1986; Ryan, 1986). However, poor record keeping and the loss of records (and maps) over time, has meant that the vast majority of the field drainage work (location and status) carried out is undocumented. This creates problems when trying to account for drained and undrained areas across soil types and land uses at national scale (O′ Sullivan et al., 2015), which can tend towards an "all or nothing" approach with little room for subtlety.

Ireland has the 3rd highest proportion of land area comprised of peat in Europe, after Finland and Estonia (Montanarella et al., 2006) and ranks highly on global comparisons in terms of peat area and peatland proportion nationally (Joosten, 2009; Xu et al., 2018). High density peatland corresponds with northern latitudes, with peatland cover ranging from about 5% in Denmark and Iceland, up to over 20% in Finland and Estonia (Joosten et al., 2017). In Ireland, the drainage of these soils contributes significantly towards estimated national emissions (Duffy et al., 2022) as currently quantified. In fact, Ireland is one of only three European Union (EU) countries (along with Denmark and the Netherlands) where the land use, land use change and forestry (LULUCF) sector acts as an emission source and not an emission sink (EEA, 2022), running contrary to stated EU policy in this sector (Romppanen, 2020). The importance of drained organic soils as an emission hotspot (IPCC, 2014; Paul et al., 2018) and the threats of climate change have focused attention on these soils (Bullock et al., 2012). Plans for their management and restoration are now a high priority, consistent with EU climate neutrality ambitions by 2050 and UN targets to limit global warming to no more than 1.5 °C above pre-industrial levels (UN, 2023). However, the lack of clarity around drainage status of organic soils introduces large uncertainty with regard to their estimated emissions. Currently, using national statistics in a Tier 1 approach, all of the 335,000 ha of the organic grassland soils mapped are assumed to be drained for the purposes of National Inventory Reporting (Duffy et al., 2022). This assumption has not been justified.

Management of grassland organic soils at farm scale will require a knowledge of the spatial distribution of organic soils, their drainage status and a range of policy instruments and measures to ensure appropriate land uses are promoted and C storage is optimised. Measures will require site-specific adaptations and practices to maintain or restore soil health and optimise functionality. Firstly, drainage of grassland organic soils is no longer advisable and secondly, soil water management (the manipulation and control of the water table) is being proposed to induce a positive change in C storage in the management regime (Teagasc, 2022; Climate Action Plan, 2023). Controlling the water table is the major lever at our disposal in managing C storage on these soils and will involve removing and blocking existing artificial drainage features in a process described as rewetting. The rewetting of peatlands, where appropriate, is seen as a fundamental priority to address peatland degradation and biodiversity loss, and to mitigate CO_2 emissions from peat oxidation and peatland fires (Parish et al., 2008). Rewetting involves the partial or entire reversal of anthropogenic drainage by reducing the average annual water table depth to close to or above the peat surface and by reducing the amplitude of water level fluctuations (Joosten et al., 2012). The IPCC (2014) defines rewetting as the deliberate action of raising the water table in soils that had previously been drained to re-establish water saturated conditions closer to the soil surface. This can be done by reducing water losses from the site by decreasing surface drainage (blocking drainage ditches (henceforth referred to as open drains), constructing bunds, or disabling pumping facilities), surface runoff, sub-surface seepage or groundwater extraction (Joosten et al., 2012; Renou-Wilson et al., 2018).

The primary objective of the present study is to examine and collate the facts, figures and assumptions pertaining to drained organic grassland soils in Ireland to establish a range of likely scenarios with regard to actual drainage status of organic soils and their estimated emissions. For that purpose, recently unearthed literature, much of which is not available in digital format, was reviewed to present national ranges indicative of drainage status of organic soils in Ireland.

2. Materials and methods

2.1. Scenario testing

A number of scenarios are presented to show the possible range of emissions, where different proportions of the total agricultural peatland area are considered to be drained to differing degrees. These emission scenarios are justified based on the arguments presented in this section with regard to the complexity of draining peat soils, the lack of technical capacity and funding for installation (and ongoing maintenance) of drainage works to achieve effective drainage at large scales and documented ranges with regard to the likely extent of peatland drainage.

2.2. The complexity of draining peat soils

In the 1980s as other parts of Europe had expanded their drainage networks, several countries including Ireland and the UK were noted as having particular drainage problems which needed more research (Mc

Afee, 1984). Drainage design in Ireland within the large scale drainage schemes was based on a generic template and not based on soil or field specific methods as in Teagasc (2022). The aim of artificial land drainage is to install drainage channels at such a depth and spacing within a given soil to control the water table at a design depth for a given crop; e.g. 0.45 m for grassland (Galvin, 1981; Brereton and Hope-Cawdery, 1988). The effectiveness of any drainage works is defined by their capacity to control the water table (Galvin, 1986b). An efficient drainage design requires detailed information on the spatial variability of hydraulic conductivity and this information is often missing in organic soil surveys or is simply outdated because of their evolution (Millette et al., 1982). Functions used to predict soil properties in mineral soil are not directly applicable to organic soils due to the nature of its composition; made up of fibric material, as opposed to the granular and structural nature of mineral soils (Galvin, 1976; Mulqueen, 1986). Peat soils are characterised by low bulk density, high total porosity that includes both large pores that can actively transmit water as well as closed dead-end pores formed by plant cell remains, varying according to plant species (Hayward and Clymo, 1982; Kremer et al., 2004). This creates a so-called dual-porosity with mobile and immobile regions (Rezanezhad et al., 2016) which means that the water table control achieved by treating organic soils the same as mineral soils is inappropriate and from a design perspective sub-optimum.

In relative terms, there was a hiatus in drainage works on both mineral and organic soils after the mid-1980s in Ireland when grant aid ceased and the EU milk quota was introduced (1984) which curtailed farm expansion and removed an incentive towards increasing the agronomic productivity of land (McDonald et al., 2014). Conaghan et al. (2000) noted that in recent times the area of blanket bog being reclaimed for agricultural purposes in the west of Ireland is relatively small due to the relatively expensive nature of the work (Burke, 1963, 1967). An increased interest in land drainage has been seen since the abolition of the EU Milk Quota (2015) and the increased demands this has put on grasslands (Läpple and Hennessy, 2012). However, it should be noted that the rate at which land is being drained would have peaked in previous decades, while todays efforts are largely reinstating/-rehabilitating drainage infrastructure in areas previously drained. The focus of land drainage related research in recent years has been on both drainage performance and environmental impacts (Ibrahim et al., 2013; Tuohy et al., 2015, 2016, 2018, 2021; Daly et al., 2017; Clagnan et al., 2018, 2020; Ezzati et al., 2020; Moloney et al., 2020; Adams et al., 2022; Byrne et al., 2022) and therefore provides a more holistic understanding of the various issues at play in an Irish context. The most recent edition of the Teagasc Manual on Drainage and Soil Management have made

Table 1
Summary of drainage design criterion for various studies conducted on peat soils.

Annual Rainfall (mm)	Peat Depth (m)	Drain depth (m)	Drain spacing (m)	Season	Mean WT depth (m)	Location	Reference
1270	NA	0.91	7.6	Winter	0.05	Ireland	Burke (1961)
				Summer	0.26		
			15.2	Winter	0.06		
				Summer	0.27		
			30.5	Winter	0.07		
				Summer	0.22		
1270	1.2–6.1	0.08	3.0	Winter	0.15	Ireland	Burke (1969)
				Summer	0.23		
		0.3		Winter	0.26		
				Summer	0.32		
		0.61		Winter	0.37		
				Summer	0.43		
		0.91		Winter	0.40		
				Summer	0.49		
1400	1.0–4.4	1 m	31	Full Year	0.35	Ireland	Farrell and O'Hare, 1974
				02/04/1970–24/09/1970	0.40		
1117–1436	4.0			Winter	0.20	Ireland	Burke (1975)
				Summer	0.45		
1250	NA	0.75	4.5		0.20	Ireland	Burke (1978)
NA	NA	0.4–0.5	10–15		0.2–0.25	Russia	Konstantinov (1980)
NA	2.4	0.28	3.05		0.38	Ireland	O Carroll et al., 1981
		0.31	1.52		0.43		
		NM	1.52		0.80		
		NM	3.05		0.78		
		NM	4.47		0.55		
NA	NA	0.70–0.80	25–50		0.30–0.50	The Netherlands	Schothorst (1982)
		0.20–0.30	12		0.0–0.30		
>2000	NA	0.5	15		0.14	United Kingdom	Stewart and Lance (1991)
		0.5	25		0.18		
NA	NA	NA	30		0.79	Canada	Hillman (1992)
			40		0.66		
			50		0.56		
			60		0.73		
1015	1.5	1	20		0.35	Canada	Prevost et al. (1997)
		1	30		0.38		
		1	40		0.28		
		1	50		0.24		
		1	60		0.23		
765–920	NA	0.5	4, 8, 12		0.21	The Netherlands	Van Beek et al., (2010)
		0.65	4, 8, 12		0.37		
1095	1.16	1.7	15		0.71	Ireland	Tuohy et al. (2018)

Abbreviations used in the table: NA = not available; NM = not measured; WT = water table.

clear the changes in national policy with regard to peat drainage stating that "further drainage of high organic content or peat soils cannot be justified", to ensure compliance with national climate change commitments (Teagasc, 2022).

The efficacy of peat drainage depends on the physical properties of the peat itself (Burke, 1972; Mulqueen, 1975) and the intensity at which artificial drainage is installed (Table 1). In the Netherlands, drainage has caused significant issues with regards to irreversible shrinkage of peats, associated subsidence and potential damage to buildings and other structures (Schothorst, 1982). Fen peats in Switzerland have suffered similar impacts (Leifeld et al., 2011). Such impacts are to be expected given the composition and mechanical properties of peat (Mohamad et al., 2022; Sulaiman et al., 2022). In many cases however, the intent to drain peats does not impose any drastic changes to the peatland hydrology over large areas in practice. The level of decomposition bears huge influence on the water holding capacity of a peat. Poorly decomposed peats have the majority of their water capillary bound, and therefore drainage, even at high intensity, has little effect (Burke and McCormack, 1969). It has been shown that the installation of drains only impacted water table depth within 0.5 m of drains in the United Kingdom (Stewart and Lance, 1991), within 2–3 m of drains in Ireland (Burke and McCormack, 1969; 1975; Holden et al., 2011). Depending on the stage of peat decomposition, the effect of drainage can extend to within 5 m of drains in hemic peat and up to 50 m from the drains in fibric peat (Boelter, 1972). A similar phenomenon, referred to as the distance decay effect was observed in China recently (Li and Gao, 2019). Furthermore, Hudson and Roberts (1982) documented that a tile drain installed in a peat had a negligible effect on the moisture content, beyond a distance of 1 m from the drain.

Galvin (1979) describes the fundamental problems associated with effective peat drainage. In peat depths ranging from 0.5 to 1.0 m, field drainage is economically infeasible. For peats deeper than 1 m, a drain spacing of 1–4 m is required. In this scenario, conventional piped drains are not cost effective so two alternatives are proposed: 1) Excavation of a tunnel, 0.38 m deep x 0.28 m wide, at a depth of 0.8 m (Armstrong et al., 1960; Grubb and Burke, 1979) or 2) The installation of a band of gravel, 0.1 m deep x 0.8 m wide, on a layer of polyethylene plastic, at a depth of 0.8 m (Burke and McCormack, 1969; Galvin, 1982). In both cases difficulties arise related to costs, installation and efficacy, but where successful, these systems give acceptable water table control during the summer months (Galvin, 1979). For optimal grassland growth maintaining an average water table depth range during the growing season from 0.4 to 0.5 m is advised (Roe, 1937; Nicholson and Firth, 1958; Teagasc, 2022). To achieve such conditions in low permeability peat, an intensive drain spacing of 3 m is needed (Burke, 1961). Such spacing's would not have been imposed widely in practice as this would require 2000–3000 m of subsurface drains per ha, which is not economically justifiable (Burke and McCormack, 1969). Burke (1969) examined the effect of a drain spacing of 3 m with varied installation depths (0.08, 0.3, 0.6, 0.9 m; 4 replicates of each) on water table position and ryegrass yields on peat soils from 1963 to 1967 in the west of Ireland (Glenamoy). Results showed that mean water table depths increased progressively with installation depth but only the 0.6 and 0.9 m installation depths could maintain the water table at the required depths during the growing season. In winter, only the 0.9 m installation achieved this target control (Table 1).

Furthermore, all systems installed, regardless of their initial effectiveness, are subject to a high degree of redundancy and poor functionality within relatively short time periods. In Sweden, it is recognised that large areas of organic soils under agriculture have been abandoned, largely due to insufficient drainage (Berglund and Berglund, 2010). Galvin (1969), in the only large scale survey of installed drainage works ever undertaken nationally (over an area of approximately 50,000 ha) found that in 24.1% of drainage works on peat, broken drains were found. It is recognised that although areas of peatland can be reclaimed with the correct technical approach, such areas will quickly revert to rushy pasture dominated by Juncus effusus if they are neglected for any length of time (Conaghan et al., 2000) as colonisation by different vegetation is known to be driven by water table depth (Timmermann et al., 2006). Furthermore, some land that remains technically, in production, has naturally rewetted due to drainage works not being maintained (Renou-Wilson et al., 2018) due to factors related to rural depopulation, increased labour and input costs and an aging rural population or because sites are remote or particularly wet and difficult to drain from a technical viewpoint (Strijker, 2005).

This challenges the assumption that organic soils are uniformly and optimally drained and maintained over time. This is especially true in Ireland as generally a sub-optimal drainage design was applied across the country, which was not sufficient to control the water table consistently throughout a parcel of land (Holden et al., 2011). Furthermore such systems were not well maintained so could not sustain their functionality over time. All of these facts run counter to the existing assumptions of drainage status of organic soils in Ireland, their associated emissions and our impression of what does and does not need water table management. For Ireland, going forward there needs to be greater research focus to overcome the large uncertainties pertaining to the drainage status of grassland organic soils and the emissions from these soils. Quantifying these aspects will establish a starting point for restoration efforts. For example, the total area of managed organic soils (those which possess an organic layer with at least 20% soil organic carbon (SOC) and a minimum thickness of 30 (Duffy et al., 2015) or 40 cm (Creamer et al., 2014)) is disputed and is estimated to range from 120,000 ha to 513,000 ha (Farrell and Boyle, 1990; Connolly, 2018). The proportion of these soils that were subjected to artificial drainage is unknown. Land drainage works typically comprise a network of open drains (relatively low intensity) acting as an outlet from an in-field drainage system (sub-surface pipes installed at relatively high intensity). Only a properly designed drainage system can control a water table at a pre-determined level that meets crop requirements e.g. grassland research proposes water table depth control at 0.4–0.5 m below ground surface for optimal yields. Furthermore, the exact drain spacing and depth required in a given field must be site and soil specific in order to control the water table at a design depth below the soil surface midway between adjacent open drains. While most of the managed grassland on peats in Ireland would have been subjected to the installation of open drains, in-field drainage would have been less common, and where applied would have utilised a generic design, due to financial and labour constraints. As a starting point, such deviation from optimal drainage design would have led to variability in the level of water table control and mean water table depth in the initial stages of land reclamation works on these soils. It must be remembered that effective lowering of the water table over wide areas is unlikely where only open drains are installed and intensive in-field drainage is required to achieve greater water table control in peat soils. In addition, all drainage systems have a limited lifespan and are subject to regular repair and replacement to retain long-term functionality (i.e. hydraulic performance and prevention of sedimentation). In practice, such maintenance requires an economic incentive, which is not always present, particularly when the historic grant-aided drainage schemes are no longer available.

2.3. National statistics on drainage status of agricultural peat soils

In Ireland, GHG emissions from an estimated 335,000 ha of drained grassland on organic (peat) soils are reported at approximately 8–9 million tonnes CO_2-equivalent (Paul et al., 2018; Climate Change Advisory Council, 2021; Duffy et al., 2022). Other European countries showing similar levels of organic soils under agriculture, Finland and Netherlands (both 330,000 ha approximately), report emissions of 8.6 and 5.6 million tonnes CO_2-equivalent respectively, while Germany recognises 1.2 m ha of such soils and associated emissions of 37.5 million tonnes CO_2-equivalent (Martin and Couwenberg, 2021). When estimating emissions from organic soils at Tier 1 of the National Inventory, it is assumed that all "managed" organic soils are uniformly artificially drained and 100% of the drainage network is functional where no information is available to counteract this assumption. Martin and Couwenberg (2021) compared how agriculturally used organic soils are included in 2020 national inventory submissions across EU countries. In Ireland, Tier 1 defaults for drainage and nutrient status are imposed (Duffy et al., 2022). However, some countries have additional measurements and can use a mixture of Tier 1 and 2 emission factors for reporting purposes. For example in Germany, Tier 2 reporting is possible due to their high-resolution and up-to-date spatial data pertaining to: organic soil mapping (includes shallow peats and areas of mixed peat and mineral soils); land use and land cover and water table position. Germany suggests that 92.3% of grassland on organic soils to be drained. Of this total 34% are shallow drained and nutrient rich with the remaining 66% deep drained and nutrient rich. The present study, based on recently unearthed information, can state that much of the 335,000 ha grassland area on organic soils, assumed in Ireland, was never effectively drained and where it was, lack of maintenance has led to natural rewetting on land that is classified technically as "in production". Herein, it is proposed that as new information is available on the overall drainage status nationally, this should be reflected in the National Inventory for Ireland. The next step would then be to apportion this figure as conducted in Germany to deep versus shallow drained and to assign a nutrient status to each of these classes.

The groundwater table in organic soils under grassland is subject to significant fluctuations due to high variability in drainage intensity (whether open or in-field drainage is installed), peat characteristics and climate (Li and Gao, 2020). Artificial drainage increases the depth and variability of the water table in the adjacent peat soil while variations in the local topography contribute to variance in the water table upslope and downslope of drainage channels (Luscombe et al., 2016). Water table depth may remain below the drainage depth (where drained) or close to the surface, depending on spatial and temporal factors. The is no national scale data available regarding water table regimes (Renou-Wilson et al., 2015) and it is this variability in water table position that results in a high degree of uncertainty regarding GHG emissions from these soils (Haughey, 2021).

In Ireland, organised efforts at draining peats were initiated with the appointment of the Bog Commissioners in 1809 who were tasked with characterising and mapping bogs and assessing "the practicability of draining and cultivating them, and the best means of effecting the same" (Horner, 2019). Extensive attempts to convert peatlands to productive agricultural land were made prior to this and likely for thousands of years with small scale conversion to grassland documented from the 1600s (King, 1685; Carroll-Burke, 2002). Increases in population and greater requirements for productive land initiated more drainage works at the fringes of peatland areas (Connolly, 2018) in the 17th to early 19th centuries, where poorer land tenants were pushed further into the bog (NPWS, 2015). Land use conversion from peatland to grassland was predominantly undertaken prior to 1845 (Connolly, 2018) in a period of agricultural expansion (Hall, 2006), when an increasing population forced the exploitation of perceived "marginal" land for agriculture. Unexploited peatlands have long been seen as a reservoir of potentially productive agricultural land (Dooley and Dickinson, 1971; McEntee, 1977; Mc Afee, 1984). Hammond (1981) proposed that over 100,000 ha of organic soils could be brought into production if subject to "proper management" where efforts could be focused on drain cleaning, outfall maintenance and the application of fertiliser.

Large-scale peatland drainage for agriculture in Ireland, was carried out in the period from the 1940s to the 1980s (Climate Change Advisory Council, 2021) and is paralleled with drainage focused literature from the 1960s to the 1980s highlighting an appreciation for the technical challenges and economic reality associated with peatland drainage. The State initiated field drainage schemes from the 1940's. A survey of land drainage schemes in the 1960s covering an area of approximately 50,000 ha showed that the drainage of peats accounted for 6.1% of the total implemented. Of these drained peatlands, 24% were drained with only open drains, while in-field drains comprised tile (sub-surface pipes, 36%), stone aggregate (13%), sod (topsod or topsoil used as fill, 21%) and bush (a type of backfill used almost exclusively in peat soils at the time comprising of scrub and brush, 5%), (Galvin, 1969). The drainage surveys and subsequent work of Galvin (1966, 1969, 1971; 1986a) offer the most complete view of drainage works at this time. The total amount of land across all soil types subjected to field drainage from the late 1940s to the mid-1980s was estimated at approximately 1.12–1.17 m ha (Bruton and Convery, 1982; Galvin, 1986a). By, 1986, of the total peatland area of 360,000 ha under agriculture, 70,000 ha was drained of which 20,000 ha required re-draining at the time, leaving a net 50,000 ha of drained peatland under agriculture. This estimate varies sharply from more recent estimates which quantify "drained", "managed" or "grassland" peats, ranging from 120,000 ha to 513,000 ha (Farrell and Boyle, 1990; Connolly, 2018), (Table 2.). The figure of 50–70,000 ha drained by 1986 represents the best estimate of drained peat soils in Ireland, as this estimate was made at the end of a 40 year period when state aid and impetus to promote land drainage works was concentrated. A similar scenario is recognised in Scotland with a dramatic reduction in new drainage works since the 1980's due to the cessation of national grant schemes (Elrick, 2019). Furthermore, other economic pressures imposed by commodity surpluses at this time meant much less demand for additional grassland (Farell and Renou-Wilson, 2019). It is still unknown, how much drainage occurred after this period to the present day as no official record or register of private drainage schemes is available, unlike the situation in many other countries. However recent estimates using earth observation methods show only approximately 80,000 ha of cultivated peats can be classed as highly productive (Green, 2020), indicating a similar drainage level to those estimates developed ≈35

Table 2
Estimated area of agricultural peatland in Ireland by different studies. Note: Galvin (1986a) is the only study that gives proportion of total area that is drained and needs re-draining.

Area ('000 ha)	Classification	Reference
120	Peat land used for agriculture: mostly occurring in poorly managed grassland on reclaimed fen peats	Farrell and Boyle (1990)
237	Managed grass on peat land excluding other grass occurring on peat and Natura 2000 designated grass.	O' Sulaiman et al. (2022)
295	Distribution of the main land use categories of peat land: Farmed Peatland in grassland	NPWS (2015), Renou-Wilson et al. (2018)
300–375	Organic Soils in Grassland	Renou-Wilson et al. (2018)
335	Organic Soils. This is the National Inventory Report. Assumed to be 100% drained.	Duffy et al. (2022)
337	Drained organic grassland soils	Climate Change Advisory Council (2021)
360	Agricultural peat land. Specifies drained fraction of estimated area is 70,000 ha (20,000 ha of this needing re-drainage).	Galvin (1986a)
370	Drained histosols (with minimum thickness of 40 cm) excluding >200 m, >12° slope and 15% drainage assumption on other grasslands	Paul et al. (2018)
420	Cultivated Peats: looks at the intersection of enclosed agricultural fields and peat soils i.e. cut over raised bog and blanket peats. Excludes: all non-cultivated peat soils (intact bogs, BNM bogs etc.), commonage areas, and forested areas.	Green (2020)
513	35% of peatlands found to be converted to grassland	Connolly (2018)

Abbreviations used in table: BNM = Bord na Móna.

years previously by Galvin et al. (1986a). There is potential for other remote methods to help in defining the extent of drained peats as established already in other regions such as Finland (Finnish Environment Institute, 2023).

2.4. Emission factors, spatial extent of agricultural peat soils and revised drainage status range scenarios

In the calculation of emissions from drained peat soils, the Irish National GHG inventory utilises a Tier 1 approach provided by the IPCC (2014) Wetland Supplement (Table 3). This approach defines that, shallow drainage imposes a mean annual water table depth of less than 30 cm below the surface and deep drainage imposes a mean annual water table depth of at least 30 cm below the surface. Rewetting is the deliberate action of raising the water table on drained soils by, for example, blocking open drains or disabling pumping facilities.

A recent large scale study by Evans et al. (2021) related CO_2 and methane (CH_4) emissions to water table depth in peat soils using eddy covariance techniques. This study estimates emission factor values much lower than the Tier 1 values currently in use. Similar studies state default emission factors may not be representative of the variety of grassland scenarios on organic soils (Renou-Wilson et al., 2014) and tend to be quite variable (Renou-Wilson et al., 2014). A recent study by Aitova et al. (2023) adds further evidence that country specific emission factors for organic soils under agriculture may be significantly lower than default Tier 1 values, when adopted. The classification of those soils spontaneously rewetted in the national inventory is also a matter for further refinement perhaps (Martin and Couwenberg, 2021). While not a key focus of this study, such changes would further reduce emissions estimates from this soil/land use category.

A number of scenarios are presented to show the possible range of emissions, where different proportions of the total agricultural peatland area are considered to be drained to differing degrees . Three emissions scenarios are presented. The calculations are performed assuming values of 300,000, 335,000 and 400,000 ha of organic soils under agricultural management. Scenario 1 represents the status quo in terms of the proportion of organic soils assumed to be subjected to drainage (Duffy et al., 2022). In Scenario 1, the total area is assumed to be drained, with 50% having a mean water table at 25 cm (shallow drained as per IPCC, 2014) and 50% with a mean water table at 50 cm (deep drained as per IPCC, 2014). Scenario 2 represents a more realistic scenario as per the issues raised in this study, with total area drained equating to 90,000–120,000 ha (30% of the total area) which allows scope for additional drainage works carried out since 1990, which are largely undocumented, but are unlikely to be at the higher end of this range, as earlier outlined. Scenario 3 represents a fully rewetted scenario. The IPCC Tier 1 emission factors are applied, with an equal share of nutrient poor and nutrient rich sites assumed. . Scenario 1–3 details are included in Table 4.

3. Results

The resulting estimated emissions for scenarios 1–3 are presented in Fig. 1. While the EPA national inventory (Duffy et al., 2022) estimates emissions in the range of Scenario 1, the reduced total area impacted by drainage, show significant potential emission reductions in all other scenarios, given the arguments presented earlier it is likely that Scenario 2 would be the most representative. Emissions from this scenario are 3.6–4.7 million tonnes CO_2-equivalent, relative to 7.0–9.3 million tonnes CO_2-equivalent in Scenario 1. Scenario 3 estimates emissions in the 2.0–2.6 million tonnes CO_2-equivalent range. The establishment and incorporation of Tier 2 and Tier 3 emission factors for the relevant land use categories into the National Inventory would further reduce emission estimates. Similarly, the refinement of data regarding other variables such as the extent of agricultural peatlands and their nutrient status would allow for further improvements in the robustness of emissions estimates.

Table 3
Emissions from drained and rewetted peat soils (Adapted from Paul et al. (2018)).

Land use	Emissions Drained [t CO_2e ha^{-1} yr^{-1}]	Emissions Rewetted	Δ Emissions
Grassland, nutrient-poor, shallow drained	23.29	3.1	20.2
Grassland, nutrient-poor, deep drained	24.08	3.1	21.0
Grassland, nutrient-rich, shallow-drained	16.67	9.9	6.8
Grassland, nutrient-rich, deep-drained	29.18	9.9	19.3

Table 4
Proportions of the total area assigned to each water table depth in each scenario. *assuming an equal share of nutrient rich and nutrient poor sites.

IPCC (2014)*	Scenario 1	Scenario 2	Scenario 3
Rewetted	0%	70%	100%
Shallow Drained	50%	10%	0%
Deep Drained	50%	20%	0%

4. Discussion

The national research agenda has focused largely on moving from Tier 1 to Tier 2 and Tier 3 emission factors within national emission inventories. However, the assumptions around drainage status of agricultural grassland peatland soils needs to be revisited. Emission calculations need to account for differences in the level of production and investment on organic soils nationally to provide more rationalised and reflective estimates. Indeed, aside from knowledge gaps related to area of these soils and the drainage status of same there are many other knowledge gaps regarding the hydrology of these systems as affected by artificial drainage and in their rewetted state.

Restoration of peat soils through rewetting diminishes GHG emissions but results in a shift in peatland biodiversity and ecosystem functioning when compared with near-natural equivalents (Kreyling et al., 2021). Rewetting, changes the hydrology of the system and can result in sharper fluctuations in the water table, inducing surface inundation onto fields with associated emission spikes (Liu and Lennartz, 2019). A greater understanding of pre and post rewetting hydrology and how this varies with peat and external properties, related to climate, topography and management is needed; this will be especially relevant in grassland peatland soils.

5. Conclusions

The total emissions from grasslands on organic soils may be overestimated due mainly, to the imposition of a simplistic assumption with regard to drainage status. A review of the literature shows that even where significant efforts and funding is targeted towards peatland drainage, the total impact is compromised by the difficulties associated with the task and the need for a high level of upfront and continuing investment to maintain effective drainage. As such, while large areas of peatland have been transformed from their natural state to grassland agriculture, there is no evidence from recently discovered historical investigations to support that effective drainage ever occurred on much land assumed, for the purposes of GHG estimates, to have been drained. Therefore a refinement of the GHG emissions associated with this land use is required. A number of other factors, currently being investigated, such as peatland extent, land use, nutrient status and associated emissions factors, are all subject to refinement over time. While potential variability in these was not included as part of the scenarios presented herein, the incorporation of refinements in these factors present further opportunities for an improved understanding of the GHG emissions from organic soils under agriculture. A significant research focus on these

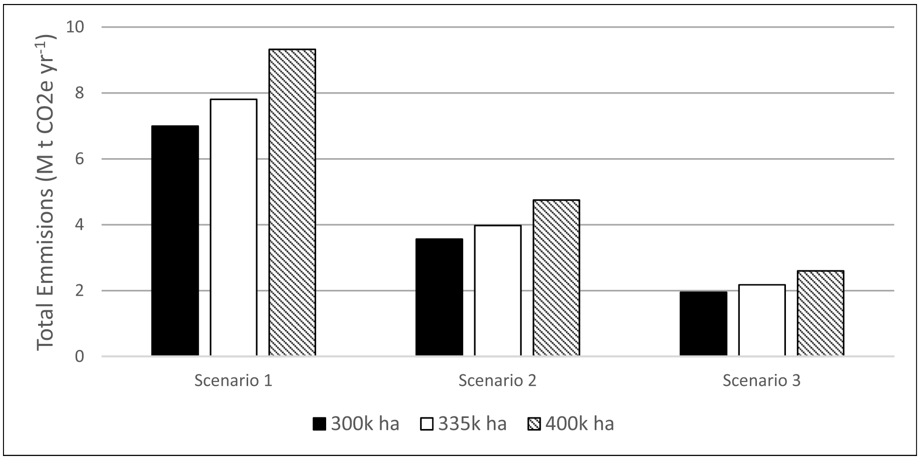

Fig. 1. Estimated emissions using IPCC (2014) emissions factors, a range of spatial extents of grassland on organic soils and a range of drainage scenarios. Abbreviation used in the figure are: S1 = Scenario 1; S2 = Scenario 2, S3 = Scenario 3.

areas is required.

The land use sector in Ireland represents a source of emissions largely driven by high levels of assumed emissions associated with drained organic soils. To harness the potential of organic soils and the scope for rewetting as a climate change mitigation tool, alternative estimations of the assumed emissions are put forward. Drainage status scenarios presented result in estimated emission savings of up to 60%. This study has proposed this potential saving by compiling a large volume of evidence to improve the wider understanding of peatland hydrology and its management.

Notwithstanding the further research needs outlined, this work has for the first time drawn on recently discovered evidence to move towards more refined estimates of the status of drained organic soils in the Irish context. The application of these findings can impact significantly on the estimated emissions from organic grassland soils and more broadly on the land use, land use change and forestry sector and can offer clarity with regard to future policy relating to, and the management of these soils.

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.

Data availability

No data was used for the research described in the article.

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