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Mapping and monitoring peatland conditions from global to field scale

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Mapping and monitoring peatland conditions from global to field scale

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Abstract Peatlands cover only 3–4% of the Earth's surface, but they store nearly 30% of global soil carbon stock. This significant carbon store is under threat as peatlands continue to be degraded at alarming rates around the world. It has prompted countries worldwide to establish regulations to conserve and reduce emissions from this carbon rich ecosystem. For example, the EU has implemented new rules that mandate sustainable management of peatlands, critical to reaching the goal of carbon neutrality by 2050. However, a lack of information on the extent and condition of peatlands has hindered the development of national policies and restoration efforts. This paper reviews the current state of knowledge on mapping and monitoring peatlands from field sites to the globe and identifies areas where further research is needed.

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It presents an overview of the different methodologies used to map peatlands in nine countries, which vary in definition of peat soil and peatland, mapping coverage, and mapping detail. Whereas mapping peatlands across the world with only one approach is hardly possible, the paper highlights the need for more consistent approaches within regions having comparable peatland types and climates to inform their protection and urgent restoration. The review further summarises various approaches used for monitoring peatland conditions and functions. These include monitoring at the plot scale for degree of humification and stoichiometric ratio, and proximal sensing such as gamma radiometrics and electromagnetic induction at the field to landscape scale for mapping peat thickness and identifying hotspots for greenhouse gas (GHG) emissions. Remote sensing techniques with passive and active sensors at regional to national scale can help in monitoring subsidence rate, water table, peat moisture, landslides, and GHG emissions. Although the use of water table depth as a proxy for interannual GHG emissions from peatlands has been well established, there is no single remote sensing method or data product yet that has been verified beyond local or regional scales. Broader land-use change and fire monitoring at a global scale may further assist national GHG inventory reporting. Monitoring of peatland conditions to evaluate the success of individual restoration schemes still requires field work to assess local proxies combined with remote sensing and modeling. Long-term monitoring is necessary to draw valid conclusions on revegetation outcomes and associated GHG emissions in rewetted peatlands, as their dynamics are not fully understood at the site level. Monitoring vegetation development and hydrology of restored peatlands is needed as a proxy to assess the return of water and changes in nutrient cycling and biodiversity.

Keywords Climate change · Nature-based solutions · Greenhouse gas emission · Organic carbon · Organic soils

Introduction

To meet the goals of the Paris Agreement, the world needs to reduce greenhouse gas (GHG) emissions by unprecedented levels over the next 8 years, and to develop methods that can remove and store carbon from the atmosphere. Nature-based solutions will be integral to this success (Seddon et al. 2021; Strack et al. 2022). Peatlands cover just 3–4% of the world's surface yet they hold nearly 30% of all terrestrial carbon (C) where it is locked in their soil (Leifeld and Menichetti 2018; UNEP 2022). Currently, about 12% of the world's peatlands have been drained and degraded through conversion for agriculture, forestry, infrastructure development and other uses, contributing to at least 4% of annual global human-induced emissions (UNEP 2022). By conserving, protecting and restoring peatlands

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globally, humanity can significantly reduce emissions and revive key ecosystems that hold the highest carbon stocks per hectare of all natural ecosystems in the world (Loisel et al. 2021).

Peatland ecosystems are very diverse as they occur across the globe from the Arctic to Sub-Antarctic and at all altitudes (UNEP 2022; Rydin and Jeglum 2013). They are commonly divided into rain-fed bogs (or ombrotrophic peatlands) and groundwater- and river-fed fens (minerotrophic peatlands), and are dominated by a myriad of graminoid, mossy, plant or tree species. Because of this diversity, peatlands provide a range of critical functions and ecosystem services essential for achieving the Sustainable Development Goals (SDGs) for e.g., livelihoods, freshwater, clean air and flood protection.

Despite their importance for the climate, people and the planet, peatlands continue to be lost at alarming rates around the world, three times faster than forests (UNEP 2022). Although 88% of countries in the world are signatories to the Ramsar Convention on Wetlands and committed to the IUCN Resolution on peatlands, many have been unable to develop national peatland definitions and policies because of a lack of information on their location, extent, and condition. More recently, efforts on peatlands policies, plans and maps were further called for by all countries during the 2019 United Nations Environmental Assembly 4 as articulated in Resolution 4/16 on the conservation and sustainable management of peatlands, including a collaboration between UNEP and Ramsar Secretariats to establish a Global Peatlands Inventory. As a result, the 2022 Global Peatlands Assessment (GPA), through the Global Peatland Initiative, was conducted to serve as a baseline for the State of the World's Peatlands and to inform upcoming global peatland inventories.

According to the GPA, peatlands extend over 500 million hectares globally across all continents, an area that is more extensive than previously estimated (UNEP 2022). However, this still may be an underestimate as peat soils can be unaccounted for under other land cover classes, particularly in Europe and Asia where they have undergone extensive land use change. Drainage, agriculture, forestry, mining and climate change are overarching threats to peatlands. The GPA highlighted the need for assessing peatlands' baseline status and regular assessment of their conditions to ensure the conservation of these important ecosystems provide multiple services globally. According to the GPA, approximately 87% of global peatlands remain in a mostly natural state—this is an opportunity to ensure that they are urgently protected from harmful economic and unsustainable developmental activities.

Most of the regional assessments in the GPA reported that there are large knowledge gaps and there remains much uncertainty (Hugelius et al. 2020; Melton et al. 2022). This paper reviews the current state of knowledge on mapping and monitoring peatlands from the field level to the globe using a variety of approaches and identifies key areas for further research. We also reflect on unsolved challenges of peatland mapping. Section "Mapping peatland extent and status" focuses on mapping peatland extent and conditions from global to national scale with case studies from nine countries. Section "Monitoring of peatland conditions" provides a plethora of approaches of monitoring from field to global scale using specific indicators and remote and proximal sensing, while including an assessment of strengths and weaknesses of key methods. The concluding section highlights current frontiers of research in peatland mapping and identifies key areas that require further research.

Mapping peatland extent and status

Multiple methodologies have been used to map peatland from field level to global extent. However, the basic components of all digital mapping studies share the same framework: the collection of data from field surveys and ancillary sources followed by mapping with the help of earth observation data obtained via remote sensing (Minasny et al. 2019; Melton et al. 2022). The availability of medium to high-resolution earth observation data from satellites, as well as cloud-based geospatial analysis platforms such as Google Earth Engine (Gorelick et al. 2017) offers the opportunity to refine our knowledge of peatland extent and status. Machine learning algorithms are also becoming more widely available and crucial components for scaling up peatland mapping efforts (DeLancey et al. 2019; O'Leary et al. 2022). Simply, peat characteristics at any location in time ($Peat_{x,y}$) can be modelled by machine learning algorithms as a

function of soil properties (s), climate (c), organisms (o), hydrology (h), and other key factors:

$$Peat_{x,y} = f(s, c, o, h, \ldots).$$

A review on digital mapping of peatland conducted by Minasny et al. (2019) shows growing interest in mapping peatlands using these technologies. Peatlands have been mapped at various scales and resolutions, with the finest site level resolution at 0.1 m and the coarsest global level resolution at 50 km. Peatlands are usually mapped as specific wetland or land cover types, and the most commonly used earth observation data include optical Landsat and Sentinel-2 and radar Sentinel-1 images, ALOS PALSAR, SRTM DEM, and LiDAR. Land cover-based assessments have the potential to miss any peatland areas that are no longer in their original land cover state but also to include as peatland ecosystems that are not systematically peat-forming. The review shows that only a few studies have explicitly mapped peat thickness and C stocks (Holden and Connolly 2011; Parry et al. 2014; Rudiyanto et al. 2018; Fiantis et al. 2023). This is a major challenge as peat thickness cannot be measured directly by remote sensing methods and cannot be easily extrapolated across areas if the detailed course of the subsoil is unknown.

Mapping and monitoring of peatlands across different scales has an impact on decisions and policies. Global and national scale maps can inform climate policy and may lead to agreements between countries, such as demonstrated by the recent Global Peatland Assessment (UNEP 2022). However, practical management of peatlands occurs at the local or field scale to the catchment scale (Fig. 1). The impact of environmental factors affecting the formation and distribution of peatlands vary between observation scales which hereby influences the choice of mapping and

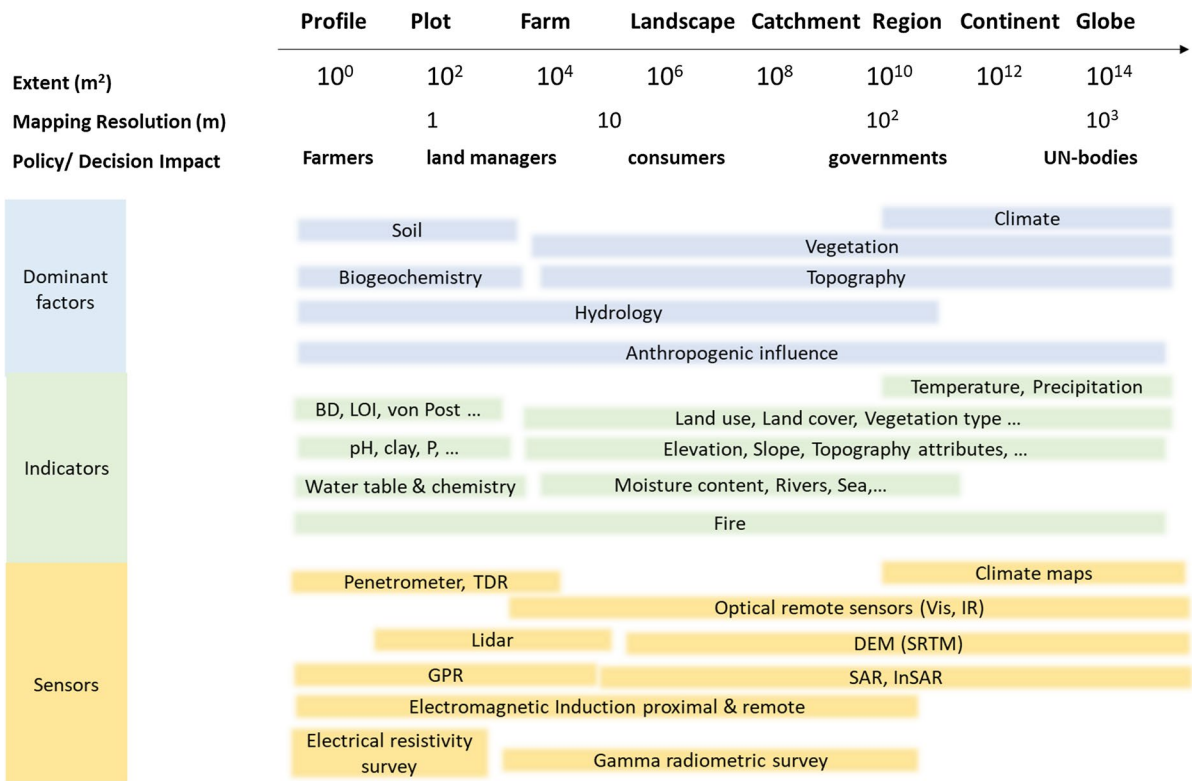

Fig. 1 Mapping and monitoring peatland status and conditions across scales. *BD* bulk density, *LOI* loss of ignition, *TDR* time domain reflectometer, *Vis* visible wavelength, *IR* infrared, *LiDAR* light detection and ranging, *DEM* digital elevation model, *SRTM* shuttle radar topography mission, *GPR* ground penetrating radar, *SAR* synthetic aperture radar, *InSAR* interferometric SAR

monitoring techniques. Global scale mapping often uses broad-scale climate and vegetation information, while the local scale can afford detailed soil information. Identifying indicators while using appropriate remote and proximal sensors can improve peat mapping at different scales. Figure 1 provides a summary of factors, indicators and sensors of peatland formation and distribution as a function of spatial scales. Climate and vegetation are important drivers to infer the peatland distribution from the global to regional scale, while topography, vegetation, and hydrogeology are important drivers at the landscape scale. At the local level, high-resolution imaging techniques such as LiDAR, electrical resistivity or conductivity surveys, radiometrics, and detailed vegetation indices (e.g., identification of tree species or functional plant groups) can be used to represent hydrology, biochemistry, and plant–soil interactions.

Nevertheless, people have the largest impact on peatland modification through land use change, drainage, climate change, and fires among other factors. In Southeast Asia, for example, the majority of peat swamp forests have been cleared, primarily for plantation agriculture and forestry since 1990 (Miettinen et al. 2016; Fiantis et al. 2023). Similar extensive conversion of peatlands has occurred in Europe since the seventeenth century. Out of the 370 Mha of northern peatlands, half are affected by permafrost and are at risk of thawing (Hugelius et al. 2020). In addition, wildfires could further enhance emissions from degraded northern peatlands by 10% (Wilkinson et al.2021, 2023) and may severely impair the water quality of adjacent water resources especially in fen peat landscapes (Liu et al. 2023). Understanding the underlying and controlling factors that impact the formation and condition of peatlands can help us to better map and monitor peatland conditions.

Global mapping

Peatlands are typically classified using hydrological, botanical, and physiognomic information, but these features disappear or are altered if peatlands are drained, converted and intensively used. Because "peat" itself cannot be mapped remotely, peatland mapping uses proxies such as topographic, geomorphic, climatic, pedologic and hydrologic features and data that can indicate the presence of peats. To date, many approaches have been used for peatland mapping (Fig. 2). At the global level, we can distinguish

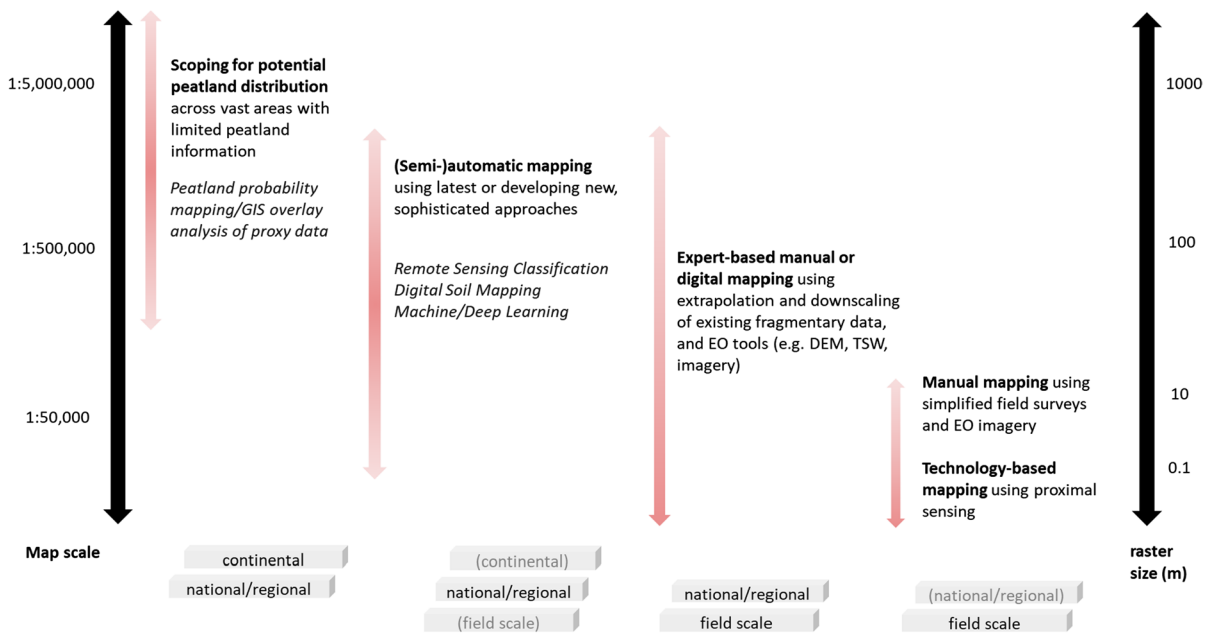

Fig. 2 Peatland mapping approaches applied according to available input information, purpose of mapping, targeted scale, methodological skills of mapper, and available funding

top-down approaches, e.g., using machine learning (Melton et al. 2022) and remote sensing (Gumbricht et al. 2017) to derive a global model, and bottom-up approaches which merge regional or national data into a global map (Yu et al. 2010; Xu et al. 2018; UNEP 2022). Top-down approaches work well when peatlands are intact, characteristic peatland features such as vegetation and its patterns still prevail, and groundwater levels are permanently at, above, or slightly below the surface. However, the accuracy and comprehensiveness of such approaches depend largely on the training data, which can be heavily biased. For example the tropical peatland map of Gumbricht et al. (2017) overlooked tropical mountain peatlands because they focused on wetlands. The best mapping results when considering different peatland types and/or boundaries between global ecological zones that differ in climate, seasonality and dominant land cover, are presently obtained with regionalised approaches (UNEP 2022).

The bottom-up approach amalgamates existing maps that were produced at the country level or at smaller scales. This approach was used in the GPA (UNEP 2022) to produce a global peatland extent map (Fig. 3). The global map consists of regionally detailed classes that can be combined to achieve the desired resolution (Arrouays et al. 2017). However, it is important to note that these map components were derived from different classification systems and input data sources. This variation in classification and data sources may impact the consistency and accuracy of the final map, with different regions having varying accuracy levels (UNEP 2022). Extensive metadata with references and information on definitions, terms and methodology, data selection and possible preparation method makes this approach transparent. Future work needs to refine this global map. Additionally, expert-assisted downscaling and extrapolation of fragmentary data can be applied to derive peatland maps at different scales.

The mapped extent of global peatlands ranges from 400 Mha in Melton et al. (2022), to 440 Mha by Xu et al. (2018), 460 Mha by Leifeld and Menichetti (2018), and 480 Mha in the recent GPA (UNEP 2022). In this latest assessment, Northern peatlands cover more than 3.0 million km^2. Many countries of the Southern Hemisphere, however, lack detailed peatland maps, although medium-sized and small peatlands are widespread. This should be the focus of future global mapping efforts.

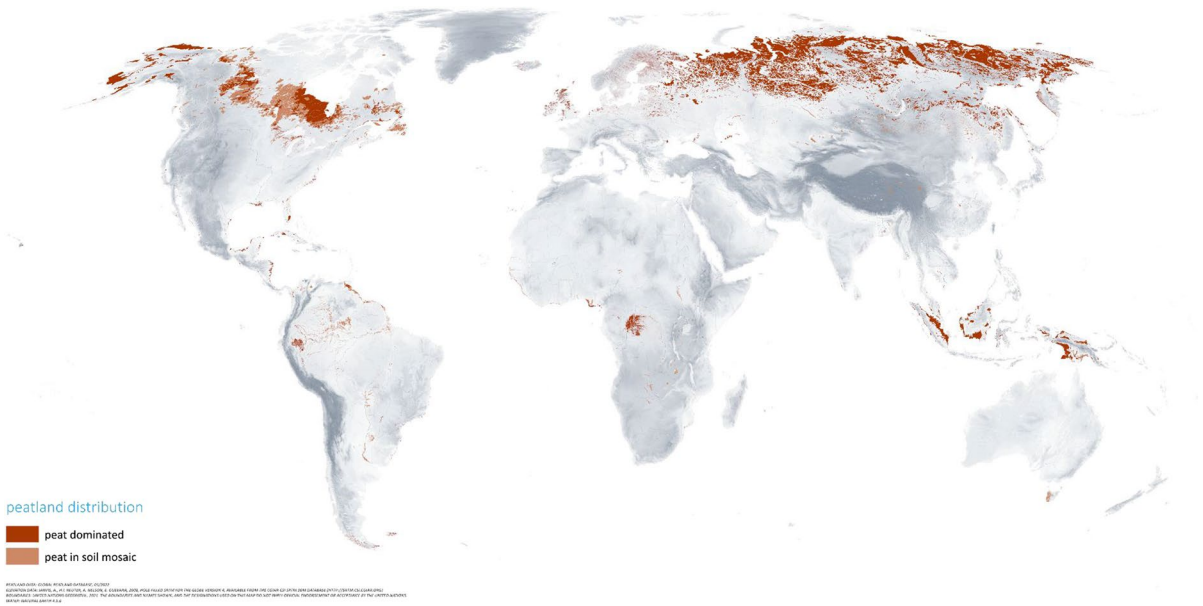

Fig. 3 The global peat-dominated area derived using a bottom approach (UNEP 2022)

Continental and national scale mapping

As awareness of the crucial role played by peatlands in carbon dynamics and soil carbon storage as well as in biodiversity and nutrient cycling has increased, numerous countries worldwide have reviewed how peatlands are managed and been motivated to establish regulations pertaining to peatlands. For example, the EU Habitats Directive and Natura 2000 network which have set objectives to safeguard Europe's distinctive species and habitats. These initiatives prioritise the conservation of intact peatlands while also striving to rehabilitate degraded ones. The EU Biodiversity Strategy for 2030 emphasises the restoration and strict protection of peatlands. New regulations at the European and national levels require sustainable management of peatlands, which necessitates refined mapping of peat soils (e.g., European Commission 2021; European Commission 2022a, b). These European regulations include the Land Use, Land Use Change and Forestry (LULUCF) European regulation (2018/814) where emissions from "managed wetlands" are included and the European Nature Restoration Law. Additionally, the EU has set a target of 55% domestic reduction in net GHG emissions by 2030 compared to 1990 levels and a national objective of carbon neutrality by 2050, which incentivizes the inventory of peatlands carbon stocks and dynamics. Furthermore, the European Commission (EC) proposed a draft for new Nature Restoration Law in June 2022 that includes binding targets for peatland restoration. The aim is net-zero CO_2 emissions from peatlands by 2050, particularly on agriculturally used peatlands. European NGOs and scientific institutions further stressed that the Good Agricultural and Environmental Conditions (GAEC2) need to ensure real protection of wetlands and peatlands, better than the degrading status quo.

To achieve these objectives, countries need to have an accurate map and effective monitoring strategies to detect peatland restoration results to support the full implementation of the proposed laws. With this in mind, this paper presents some recent advances in peatland mapping using remote sensing and digital mapping methods with case studies from nine countries. It is not meant to be an exhaustive review, but rather we aim to summarise and highlight the mapping status, uniqueness, and approaches available to address policy implementation.

Canada

Canada is characterised by one of the largest peatland carbon pools worldwide, mostly distributed within the boreal biome (UNEP 2022). A small portion (< 2%) of the total extent was drained and cultivated (1.3 Mha), affected by oil extraction or mining, flooded by hydroelectricity reservoirs, impacted by forestry or human development, and to a small extent by peat extraction. However, these statistics do not consider peatlands near urban areas that face higher pressure than those in remote locations. Therefore, mapping efforts are crucial to estimating carbon stock and understanding how to mitigate the effect of climate change and anthropic activities on peatland ecosystems. Regulations are implemented on a provincial and territorial basis. For instance, Quebec adopted a wetland conservation policy in 2017 that regulates land-use planning. Regional plans must include a mapping component for wetland zones.

The map of Tarnocai et al. (2011) remains widely used as a basis for other mapping projects such as the Global Peatland Map of GPA (UNEP 2022). Canadian studies at the provincial or regional scale with mapping components published in the last 5 years aimed at tracking peatland changes over time or were related to agricultural use and conservation. For instance, recent articles focused on regeneration after wildfires or smouldering fire potential (Wilkinson et al. 2021; Enayetullah et al. 2022), permafrost thaw-induced changes (Carpino et al. 2021), and carbon stocks estimations (Primeau and Garneau 2021).

Recent studies leveraged the digital soil mapping workflow for mapping peatlands. For instance, DeLancey et al. (2019) employed machine-learning algorithms and remote sensing covariates to generate a probability map of boreal peatlands. Sothe et al. (2022) utilised machine learning methods mapped the soil organic carbon content, including peatlands, across Canada. Deragon et al. (2023) focused on mapping around 9000 hectares in southern Quebec to derive the arable peaty layer thickness while considering limnic materials. The goal was to facilitate soil conservation interventions by delineating management zones for drainage and biomass crop amendments, limiting soil degradation (Dessureault-Rompré

et al. 2020). Proximal sensor data fusion and remote sensing covariates were used at field-scale to predict chemical and physical properties, or peat thickness (Ji et al. 2019). Other studies have successfully mapped soil water available capacity (Lafond et al. 2015), bulk density, organic matter content, saturated hydraulic conductivity, peat thickness, and the depth of the compacted layer (Hallema et al. 2015) by employing comprehensive soil sampling schemes to characterise the evolution of these soil properties following the conversion of peatlands to agricultural use.

Despite this progress, Canada is facing a lack of data to support policymakers to establish policies to protect the peatland resources. Some remote locations in northern Canada, mountain areas and forested peatlands, still need to be accurately sampled and mapped (UNEP 2022). Moreover, standardising data from provinces with varying levels of detail has proven to be challenging. Federal agencies are leading the way, but better coordination between provinces is required to achieve this goal. Since peat thickness was mostly mapped at the regional or field scale, efforts to provide estimates at the national scale are critical to evaluating the vulnerability of peatlands to climate change-related droughts (Moore et al. 2021) and to better estimate carbon stocks. Thus, national and provincial mapping products are needed to use the available data from the industry, universities, and provincial government to its full potential.

Finland

Finland had originally 10.2 Mha peatlands, 30% of the country's land area. About 55% of the peatland area is drained, predominantly (93%) for forestry (Turunen and Valpola 2020). Unlike cultivated peat fields or peat extraction areas, in 2021, the drained peatland forests were still an overall net sink of 0.2 Mt CO_2 due to the increasing carbon stock of trees and due to the northern soils that sequester more carbon than they release to the atmosphere on an annual basis. However, the net ecosystem CO_2 sink of drained peatland forests has been diminishing due to increasing harvests (Alm et al. 2022).

The emission levels depend on the fertility status of the peat, with more fertile peat producing greater emissions (Minkkinen et al. 2007). To obtain more accurate GHG inventory results, it is necessary to have updated information on the area of organic soils covered by agriculture and artificially drained forests as well as active and abandoned peat extraction areas. These land uses are considered in the national GHG inventory under the LULUCF sector (Statistics Finland 2022). Additionally, detailed biodiversity mapping is essential for the protection planning of the most vulnerable types of peatland, such as meso-eutrophic fens and spruce swamps.

In 2021–2022, the Advances in Soil Information—MaaTi project produced a comprehensive high-resolution peatland GIS database for the entire country. This database contains information on peatland site types and their fertility status according to the Finnish classification system (for details of peatland site types, see Päivänen and Hånell 2012; Laine et al. 2018; Turunen and Valpola 2020), as well as drainage status and current land use. The machine learning approach used a combination of satellite data, airborne laser scanning, geophysical data, and various GIS datasets to classify the land cover status in 2000–2021. Mapping was accomplished within the boundaries of the existing peatland boundaries, field parcels adjacent to them and peat extraction sites retained in a topographic database version published within 2005–2020 by the National Land Survey of Finland.

Classification of all 39 forestry-drained peatland site types was challenging, overall accuracies ranging 29.3−40.4%. Accuracies increased to 51.9−57.5% when the drained site types were reclassified into five fertility level classes, relevant for GHG inventory. The respective overall accuracies were higher for undrained classes; 32.6−49.3% for site types and 46.6−66.5% for their fertility level classes. Moreover, land cover classification of the peat extraction areas to peat, vegetation, forest and water was highly successful with 86.9% producer's and 89.1% user's accuracies.

The final map, which covers the entire country, is in a 10-m pixel raster resolution and includes three data layers: site types and peatland land use (Fig. 4), fertility levels, and land cover of the peat extraction areas. The database is scheduled to be published in 2023 and will be available for viewing and downloading at www.geo.fi. As of 2021, 35,000 hectares of peatlands were under restoration. Thus, regular updates of the database are necessary.

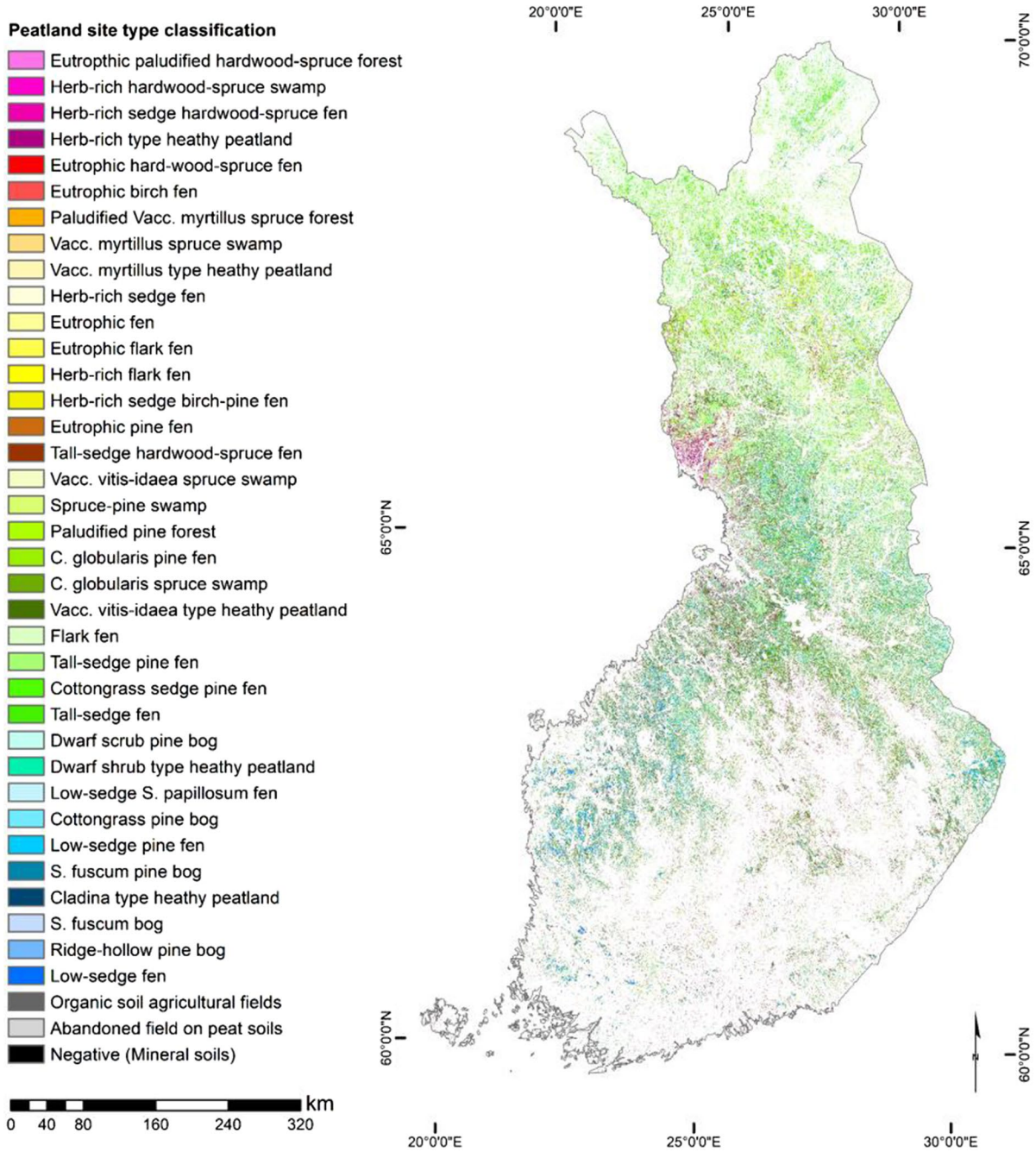

Fig. 4 Peatland site type map of Finland

Norway

Peatlands in Norway have traditionally been and are considered an important resource for agriculture, forestry, and growing media. In the early 1900s, a national body was established to map and develop peatland areas for peat extraction, as an attempt to address poverty and reverse the loss of labour to America. In the 1960s, a national survey was conducted to identify areas with potential for agriculture

and forestry. This survey covered all land below the tree line in Norway, which is about 59% of the country's land area, and was completed in the late 1980s (Bjørdal 2007). The results were made available digitally through the Digital Markslagskart (DMK) mapping system, which defined peatland as areas with peatland vegetation and at least 30 cm of peat. After 2008, DMK was replaced by AR5 map (1:5000 scale), which is a simplified mapping layer that lacks some of the detailed peatland information provided by DMK (Ahlstrøm et al. 2019).

Despite being simplified, AR5 provides detailed extent information for individual peatland areas across Norway. However, it contains systematic gaps and uncertainty because the mapping effort focused on potentially productive lands, and national maps exclude peatlands found above the tree line or within other marginal regions. Efforts were made to address the gaps with field mapping through the use of N50 (1:50,000), which is a full coverage national topographic map, where wetland areas were defined through classification of aerial photos. This was developed into the mapping layer AR50, which incorporates information from AR5 below the tree line and combines N50 and remote sensing, utilising Sentinel-2 satellite imagery, above the tree line (Fig. 5).

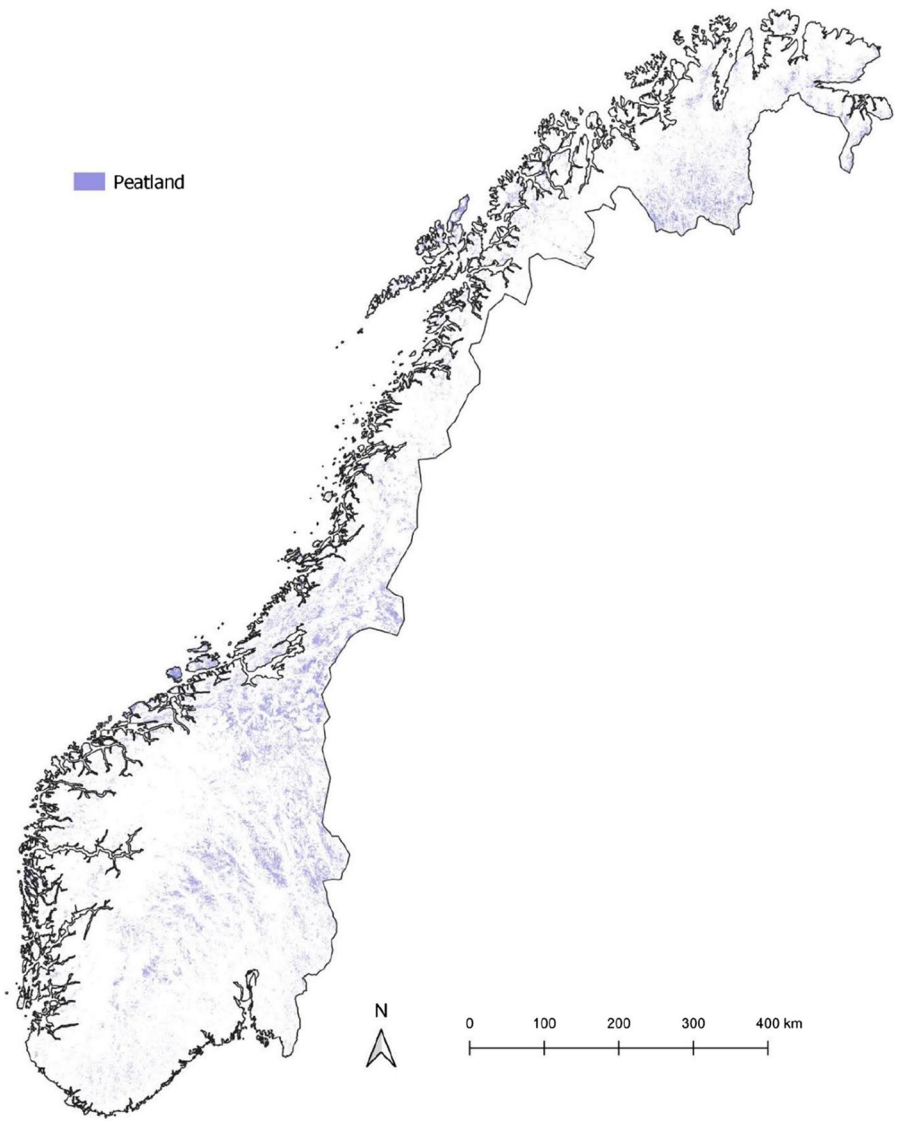

Fig. 5 Distribution of currently mapped peatland in Norway (*Source* AR50). According to AR50, this map shows discrete areas of peatland meeting the strict definitions for peatland areas (see Table 1)

These mapping layers provide the basis for regional and national land use policies and planning and are valuable to the national GHG accounting. This presents challenges because functional peatland definitions may underestimate the extent of the national resource of carbon rich soils. Based on these mapping resources, the extent of peatland in Norway is approximately 5.8% of the terrestrial land area. More recently a national area frame study (AR18X18) challenged this value, proposing a total wetland area of 2.88 ± 0.18 Mha, which could significantly increase the estimates for peat soils in Norway (Bryn et al. 2018). As opposed to AR5, which was a resource mapping of productive regions, this was an ecological mapping encompassing the whole Norwegian land area. This study followed the design of the Land use/Land cover agricultural survey (LUCAS) programme developed by the EU. This technique used a random sampling design with field survey followed by national mapping. The mapping was an ecological assessment based on vegetation communities, which were classified according to VK25, a Norwegian vegetation classification system (Rekdal and Larsson 2005; Rekdal and Bryn 2010). This survey identified significant gaps in the mapping of peatlands in the highlands and in central and Northern Norway. Based on this new assessment, mire and wetlands cover was re-estimated to account for 8.9% of the land area in Norway. However, these estimates are regional estimates with a relatively low resolution compared to the national mapping resources provided by AR5 and AR50. In addition, this assessment was ecological and therefore would not have classified sites without typical wetland plants as peatlands. It excludes drained organic grasslands and productive forestry on drained peatland.

Due to the strict functional definition of peatlands in AR5, changes in land management can result in an apparent rapid rate of attrition of peatland area due to re-classification. However, carbon loss following drainage of peatland is not instantaneous and many previous peatland sites may still contain substantial organic carbon. AR5 is partly updated by municipal authorities who are more likely to report the change in category from peatland to other land uses but may fail to alter the definition once the site is abandoned. This limits policies aiming to restore peatlands or to preserve the organic carbon that may still be stored in these soils.

Ongoing efforts to enhance peatland mapping in Norway center around employing advanced technologies and tools to overcome limitations faced by traditional techniques. Remote sensing and machine learning algorithms have become more prominent for better estimates of peatland extent (Bakkestuen et al. 2023). Additionally, geophysical methods involving aerial electromagnetic technologies are being explored to improve peatland thickness mapping (Silvestri et al. 2019). Nonetheless, none of these methods by itself offer a complete solution for determining national peatland coverage. To address this, the future of peatland mapping in Norway calls for a coordinated approach that integrates multiple techniques and technologies.

United Kingdom

In the United Kingdom, around 10% of the total land area is covered by peatland, much of which is degraded due to historic drainage, extraction, overgrazing, air pollution, use as cropland and/or afforestation (Evans et al. 2017). There are further extensive peat deposits in UK Overseas Territories, many of which are under mapped and with a relatively poorer understanding of their current condition (Evans et al. 2017; Artz et al. 2019a, b). Efforts to map the area of peatland using either traditional soil surveys techniques coupled with expert opinion-based extrapolation or remote sensing-based modeling are still resulting in considerable variation in the estimates of the total peatland area (Fig. 6). For example, while the currently adopted peatland map in the UK Greenhouse Gas Inventory submissions uses a model returning a total of just below 3 Mha for the combined total in Northern Ireland, Scotland, England and Wales, and a further 0.28 Mha in Overseas Territories and Crown Dependencies, other mapping efforts, particularly for Scotland, Northern Ireland and the Falkland Islands suggest that improvements on these estimates may still be required (e.g., Aitkenhead and Coull 2019).

In terms of the condition of the UK peatlands, current estimates suggest that only 22% of the former peatland area is still in a condition compatible with carbon accumulation (Evans et al. 2017). Of this 22%, the majority of the peatland types still in good ecological condition are blanket bog areas, with lowland raised bog and fen habitats having

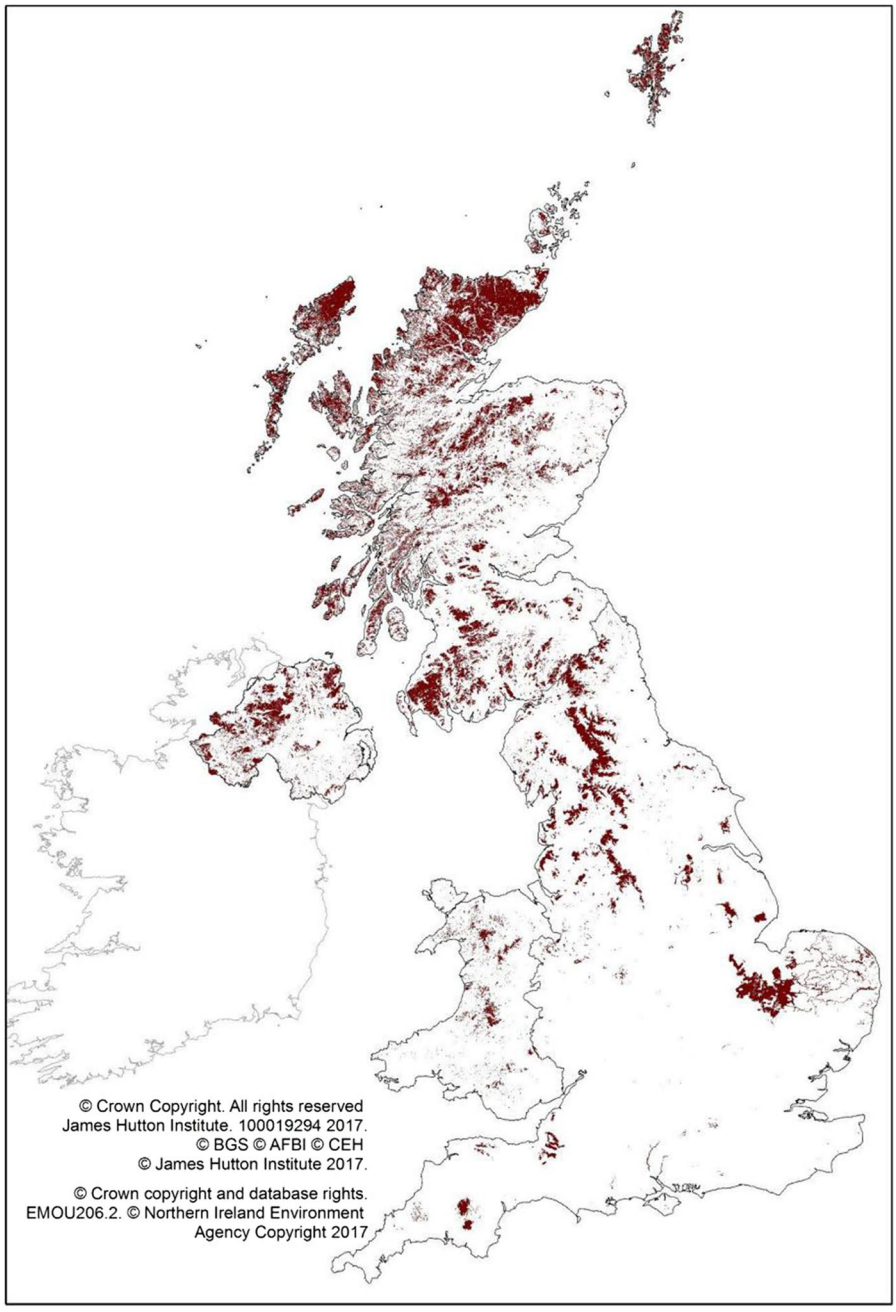

Fig. 6 Peatland map of the United Kingdom exclusive of Overseas Territories and Crown Dependencies. Peat extent as shown is based on various survey and model-based data sources, with both known and unknown limitations in terms of local accuracy. *Source* Evans et al. (2017)

been much more damaged and estimates of degradation reaching over 90% of these. A set of large-scale programs to restore peatland is underway across the UK, with around 0.1 Mha restored to date through a mixture of largely publicly funded work, but increasingly also private investment is beginning to aid in the efforts to increase annual restoration rates.

Mapping and monitoring of peatland condition was traditionally limited largely to nature designated areas, and still uses field-based methods to assess condition on the basis of vegetation characteristics and other indicators of damage, such as degree of browsing, indicators of recent burning, or drainage and erosion features. National statistics are therefore somewhat biased by the fact that nature designated

areas for peatland habitat interests were designated as the better examples of particular habitats in the first place and therefore there is growing interest in the use of remote sensing for monitoring of peatland condition (Lees et al. 2018).

The International Union for Conservation of Nature (IUCN) UK Peatland Programme has recently updated the Peatland Code, a tool aimed at enhancing the restoration and conservation of UK's peatlands. The Peatland Code allows landowners with eligible, degraded peatlands to produce carbon units through restoration action. This effort has led to an emphasis on mapping the location and condition of peat in the UK to allow the restoration work to be prioritized more effectively. For example, in Scotland, efforts are being made to improve the current 100 m resolution digital soil map to 10 m across the whole of Scotland, mapping the thickness and carbon stock of peatlands.

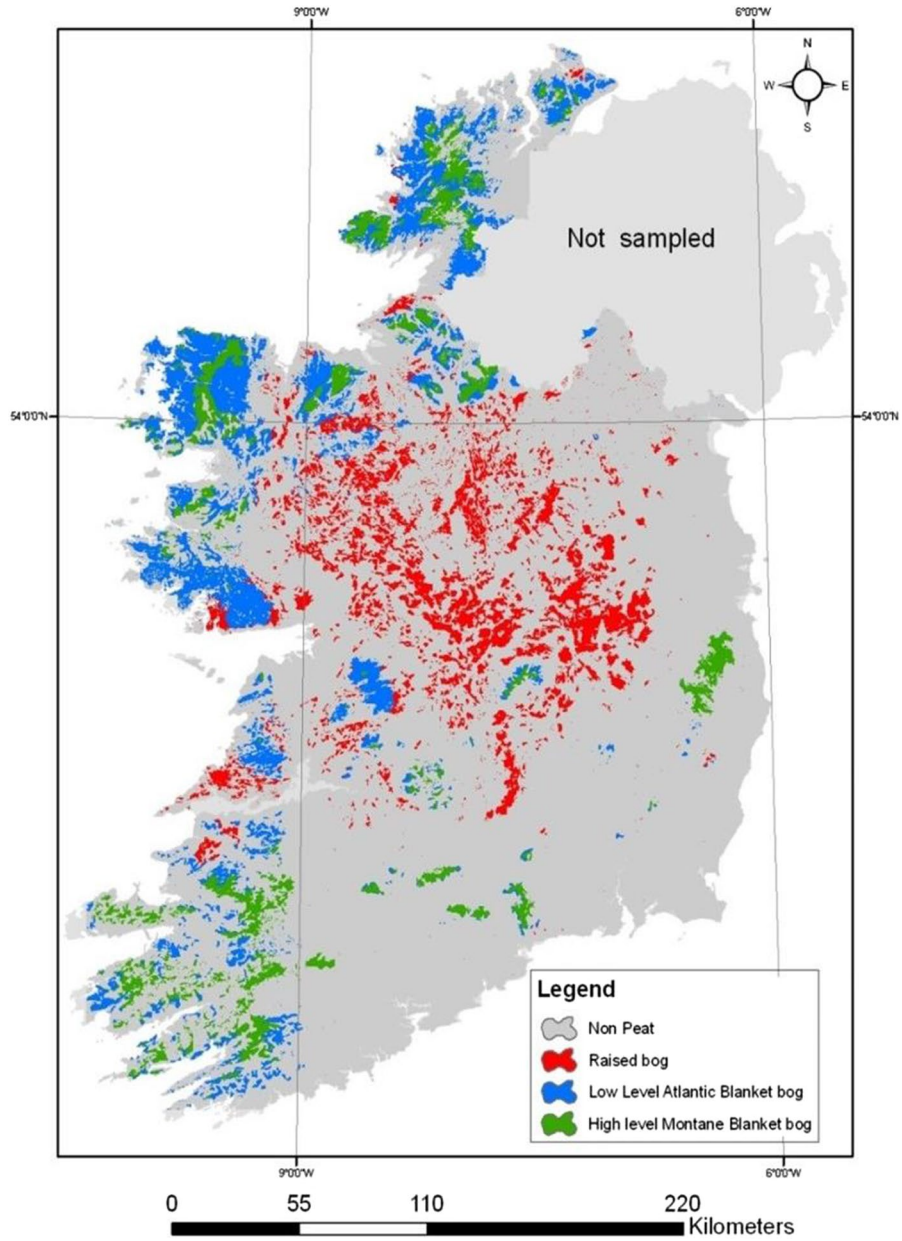

Fig. 7 Peatland map of Ireland (Connolly and Holden 2009)

Ireland

In Ireland, peat soils cover about 20.6% of the country (Connolly and Holden 2009) (Fig. 7) and contain ~ 2216 Mt C (Renou-Wilson et al. 2022). There are two main types of peatland in Ireland: raised and blanket bogs with a very small area of fens. The oceanic blanket bogs are globally rare, but abundant in Ireland (Connolly and Holden 2009) and about half of Europe's raised bogs are in Ireland. These ecosystems have been mapped for over 200 years in Ireland, with the Bog Commissioners producing some of the first accurate peatland maps. Those maps accounted for about 30% of all Irish peatlands were developed from 1809 to 1814. Hammond (1981) developed a definition for Irish peatlands and produced *The Peatland Map of Ireland*. That definition was adjusted to facilitate mapping by Connolly et al. (2007) and Connolly and Holden (2009). Their definition stated that a peatland must contain peat, a sedentarily accumulated organic soil material with at least 30% organic matter, have a depth of 30 cm on drained and 45 cm on undrained areas and cover at least 1 ha (Connolly and Holden 2009). However, in the GPA (UNEP 2022), it was recommended that shallow peat soils greater than 10 cm in depth should be included in peatland maps. As such, a new iteration of the Irish peat map is being developed to, including shallow peatlands. Preliminary results indicate that this increases the peatland extent for Ireland to about 23.3% of the country.

Land use on Irish peatlands is similar to the UK, and are highly degraded due to drainage, land use conversion, over grazing and peat extraction and now only 5–15% remain in a near natural condition (Fluet-Chouinard et al. 2023; Connolly 2018). The process of peatland degradation began early in Ireland with King (1685) making suggestions on how to drain them, probably for conversion to agriculture or to be cut by hand for fuel. By 1809, some areas had been converted and mapped on the Bog Commission maps as "grass on bog". The largest land use change over time has been the conversion of peatlands to grasslands (~ 430,000 ha) (Connolly 2023). In the twentieth century this process of degradation accelerated with the mechanization of peat extraction for fuel (i.e., Bord na Móna and domestic extraction) and to facilitate widespread afforestation (Connolly 2018). While Bord na Móna ceased peat extraction in 2019 (Habib and Connolly 2023) and 30,000 ha of its land is undergoing active rewetting, rehabilitation and restoration (Bord na Mona 2023), several companies are still extracting peat and widespread mechanical extraction for domestic purposes still occurs.

The centuries of land use and land use change has created a spatially complex heterogeneous peatland landscape that is emitting large amounts of GHGs (Connolly and Holden 2011; Aitova et al. 2023). However, there is considerable uncertainty around these emissions. The Government of Ireland tracks emissions from "managed wetlands" which comprise about 5% of the total peat area (LULUCF reporting). However, "unmanaged wetlands" are assumed to be "natural" and "unexploited" and therefore not emitting (Duffy et al. 2022) but it is clear from satellite imageries that this is not the case due to wide scale degradation. The predominant land use changes in Ireland since 1990 have been peatland to grassland or forestry (Connolly 2018; Habib and Connolly 2023). These are then accounted for as "grassland on organic soil" and "forestry on organic soil" (Hyde, B. Pers. Comm.) and Tier 1 emission factors (EF) are applied for LULUCF reporting, with some exceptions (Aitova et al. 2023). Both Aitova et al. (2023) and Tuohy et al. (2023) state that the Tier 1 EFs for grassland (on peat) for Ireland overestimate emissions due to assumptions about management practices and drainage density/status, however, both may underestimate the area of converted peatlands (Connolly 2018; Green 2020). Aitova et al. (2023) developed country specific EFs for Ireland and estimated that these land use types as well as peat extraction areas account for emissions of 8.4 Mt CO_2-eq per year (excluding horticulture and combustion). These values could form the basis of Tier 2 EFs reporting from Irish Peat. They also state that improved mapping could improve the robustness of national emissions reporting, particularly for grasslands.

The decision tree (DT) approach to mapping peatlands by Connolly et al. (2007) facilitates the integration of new data sources over time leading to improvements in the robustness of emission reporting mentioned by Aitova et al. (2023). That approach has led to a continual refinement in peatland mapping in Ireland with a new map developed by Connolly and Holden (2009). A third iteration is in preparation by Gilet and Connolly which identifies an additional ~ 200,000 ha of peat soil. Future iterations will include the radiometric work by O'Leary et al.

(2022) and the accurate historic maps digitized and geo-rectified by Morley et al. (pers. com). These peat maps facilitate the use of earth observation to track and monitor peatland land use and change over time (Woodcock et al. 2020). Landsat data and machine learning have been used to track land use change on peatlands in 1990, 2005 and 2020 (Habib and Connolly 2023). Ingle et al. (2023) uses high resolution imagery to upscale CH_4 fluxes and another study uses Sentinel-2 imagery to quantify land use and CO_2 emissions on Irish raised bogs. Remote sensing when combined with peatland maps illustrates the temporal dynamism of these ecosystems. These methods may be used to facilitate more robust reporting and facilitate Tier 2 and possibly Tier 3 reporting.

Denmark

Denmark's contemporary peatlands cover 173,000 ha and emit approximately 5.4 Mt CO_2-eq per year, the largest component of these emissions originating from drained cultivated peatlands thus making them the largest source in the agricultural sector (Nielsen et al 2022). The Danish Council for Climate Change has suggested that restoration could potentially reduce these emissions by 4.1 Mt CO_2-eq. In 2021, ministerial agreements were launched to rewet 100,000 ha of peatland areas by 2030, with the aim of mitigating GHG emissions and improving biodiversity. Mapping peatlands to identify priority areas with the largest GHG reduction potential is crucial to reaching Denmark's national target of a 70% reduction in GHG emissions by 2030.

In Denmark, historical peatlands were estimated to cover approximately 230,000 ha (Greve et al. 2014). The first attempt at mapping peatlands aimed at assessing the quality and potential use of bog resources for fuel due to failed supply of foreign fuel during World War I (Thøgersen 1942). The Danish Land Development Service then classified meadows and bogs larger than five hectares into four groups depending on the quality of the peat for fuel from the early 1920s (Thøgersen 1942).

Since 1975 organic soils have been sampled within different national soil inventories (Greve et al. 2014; Gomes et al. 2023). Using legacy soil data and classification tree algorithms, Bou Kheir et al. (2010) delineated mineral and organic soils within the Danish cultivated wetland areas. The resulting map shows organic and mineral soils covered 182,000 and 392,800 ha of the total cultivated wetlands, respectively.

Greve et al. (2014) further investigated the change in cultivated peatland extent comparing maps generated from historical or contemporary organic samples with geostatistical methods. The study determined a 35% reduction in the extent of Danish cultivated peatlands between 1975 and 2010 which could be linked to the effect of drainage and historical peat extraction for fuel.

Responding to GHG mitigation, the ReDoCO2 project (https://redoco2.net/) aims to develop an overall methodology to map peatlands in detail and deliver accurate estimates of CO_2 emissions and potential carbon stocks in Denmark. Combining state-of-the-art modelling and interpretation techniques, proximal and drone-mounted geophysical sensors, and 3D software, the project will provide decision-makers with detailed information and cost-effective tools to appropriately select which peatlands to restore. Preliminary digital maps of soil organic carbon content (Fig. 8) and peat thickness have been generated over the whole Danish wetlands at 10-m resolution. This project tested available environmental data (e.g., soil, geology, landscape, climate, LiDAR- based topography, Sentinel-2 and Sentinel-1 data) to provide baseline maps created using machine learning and deep learning methods. The project also investigated different geophysical sensors over pilot areas located in fen and bog peatlands (from 10 to 135 ha), which will be discussed in detail in Sect. "Field scale monitoring".

Moreover, the upcoming TargWET project will combine existing environmental data with new data on emissions, soil microbiology, vegetation, and soil functional properties such as soil–water retention, gas-phase transport, and soil hydrophobicity. Merging these datasets within advanced modelling methods will enable precise delineation of the hotspot areas for CO_2 emissions within drained agricultural peatlands.

Mapping activities will also greatly benefit from several ongoing monitoring studies investigating the consequences of rewetting peatlands in terms of GHG balances and water quality. Finally, recent projects have also aimed at revisiting 1000 sampling locations from 2010 to estimate the variation in peat thickness and soil organic carbon content, and collecting new data from shallow peat areas (~1000 locations) in order to improve models. The updated maps of peat

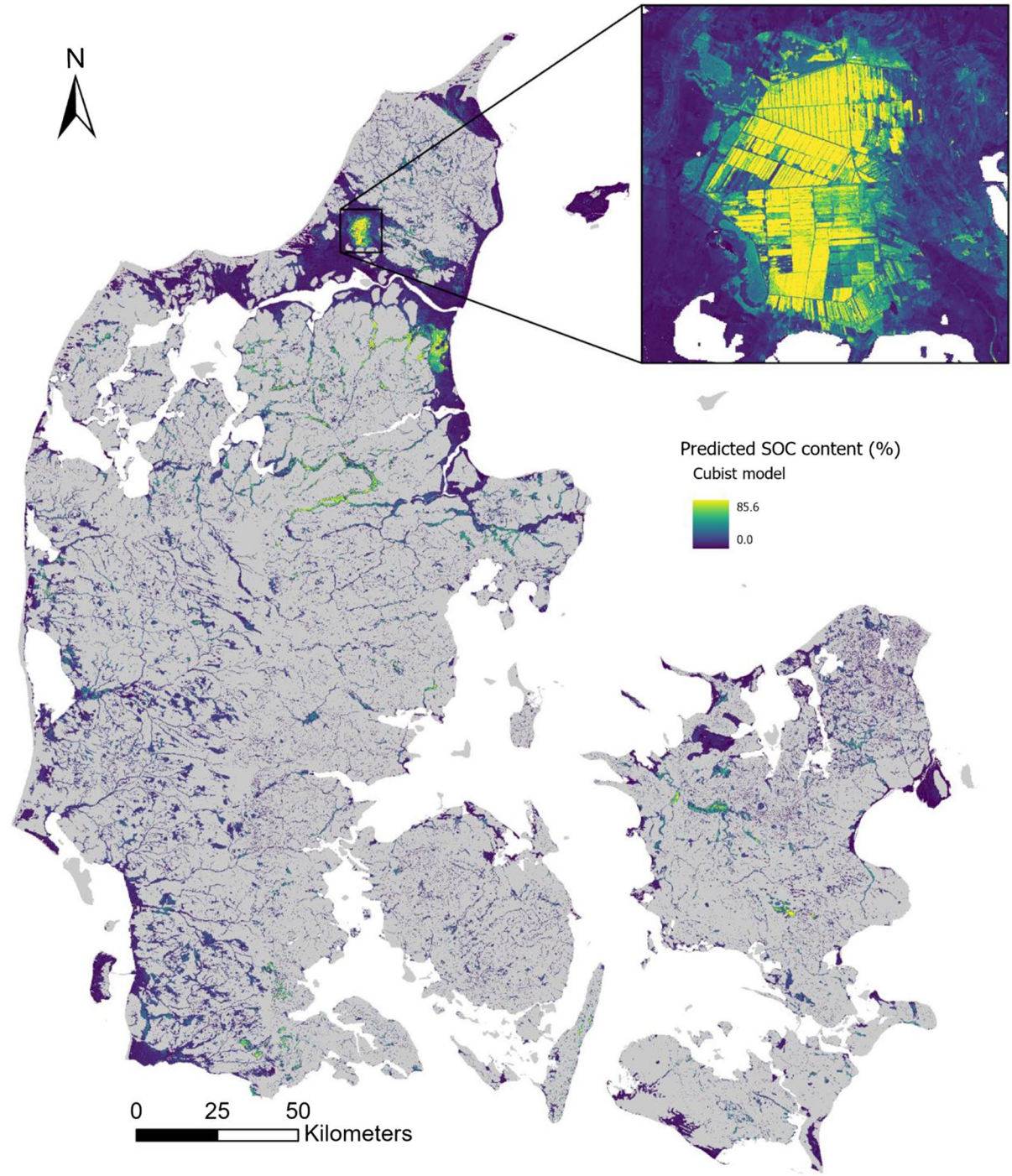

Fig. 8 Preliminary map of soil organic carbon content (SOC in %) in Danish wetland areas generated using cubist regression tree model, with details displayed for the Store Vildmose raised bog area

extent, thickness and soil organic carbon content are in progress, and will be available by the end of 2023.

Austria

Austria is a small, landlocked country in Central Europe covering 8.387 Mha. Despite its small area, many different landscape settings that favoured peatland development are found in the Alps and prealpine regions, the Bohemian massif and the Pannonian basin. These differing landscape settings have resulted in different land use intensities and different approaches to land use. In the Alps, valleys are often cultivated intensively as grassland or croplands. On mountain slopes or in high altitude locations, meadow use dominates, but there, pristine peatlands can also be found. In pre-alpine settings as well as the Pannonian basin, almost all peatlands are intensively cultivated and in the Bohemian massif, forestry on peatlands dominates. These differing land use patterns require different approaches to the mapping of peatlands.

International discussions on climate change and peatlands, and EU regulations have pushed for the inclusion of managed peatlands in agricultural and environmental policies, increasing the need for better knowledge about peatland coverage in Austria and the formation of a national alliance in Austria to protect peatlands.

Until the first half of the twentieth century, a main incentive for mapping peatlands was to assess the suitability of sites for peat extraction (k. k. landwirtschaftlich-chemische Versuchsstation in Wien 1911). Later mapping efforts were driven by the need to assess the suitability of the soil for agricultural purposes. This mapping effort is the basis for current digital soil maps (www.bodenkarte.at). Peatlands in forests have not been mapped systematically. In the 1980s, intact peatlands were systematically mapped for nature conservation purposes (Steiner 1982), but this nature-conservation driven documentation is likely incomplete and maps areas with peat forming vegetation and not peat soils.

This situation resulted in imprecise and unclear information of the peatland area in Austria. Essl and Steiner (2017) report the uncertainty on peatlands area, possibly exceeding 120,000 ha. Austria's mire strategy (Schröck et al. 2022) distinguishes peat soils and mires and estimates an extent of 30,000 ha for mires and at least 50,000 ha of peat soils, acknowledging that this may be a severe underestimation.

The PeatGov Austria research project is working on evaluating the accuracy of the Austrian map of soils used for agriculture, called ebod2. The project is collaborating with the Environment Agency Austria, which is compiling various databases related to peat soils and wetlands to update the information on Austrian peat soils.

Peru

While Peru ranks among the top peatland countries in the tropics (Gumbricht et al. 2017), there is to date no national map. Peatlands occur on the coast, in the Andes and in the Amazon basin, with the greatest extent in the later (López Gonzales et al. 2020). The significant peat deposits of the Peruvian Amazon play a crucial role in the global, regional and national climate. One of the most widespread peat-forming ecosystems in the region is the palm swamp, dominated by the *Mauritia flexuosa* palm. These palms are frequently harvested by cutting female palms, which threaten this ecosystem and may turn it from a natural carbon sink into a source. To assess the C stock and level of disturbance in the area, the distribution of degradation and deforestation in palm swamp peatlands in Peru was mapped.

Remote sensing technologies, such as Landsat, ALOS-PALSAR, and GEDI, were used to produce land cover maps from 1990 to 2007 and 2007 to 2018 in a 28 Mha area. A local peat map (Hastie et al. 2022) was used to filter the area, and peatland carbon reserves were calculated using default carbon densities (Draper et al. 2014; Hergoualc'h et al. 2017; Honorio Coronado et al. 2021) in peat-forming ecosystems (palm swamp, herbaceous swamp, and pole forest). Degradation was defined as transitions of palm swamps from higher to lower canopy density, while deforestation was defined as transitions from palm swamps to herbaceous swamps. Emissions were computed from the areas of transitions, empirical peat emission factors (Hergoualc'h et al. 2023), and biomass changes.

The estimated carbon stocks in the predicted peat-forming ecosystems were 3.88 ± 0.12 Pg C, taking into account both peat and biomass. Over 1990–2018, an area of disturbance of $535{,}423 \pm 8419$ ha was observed, with most of

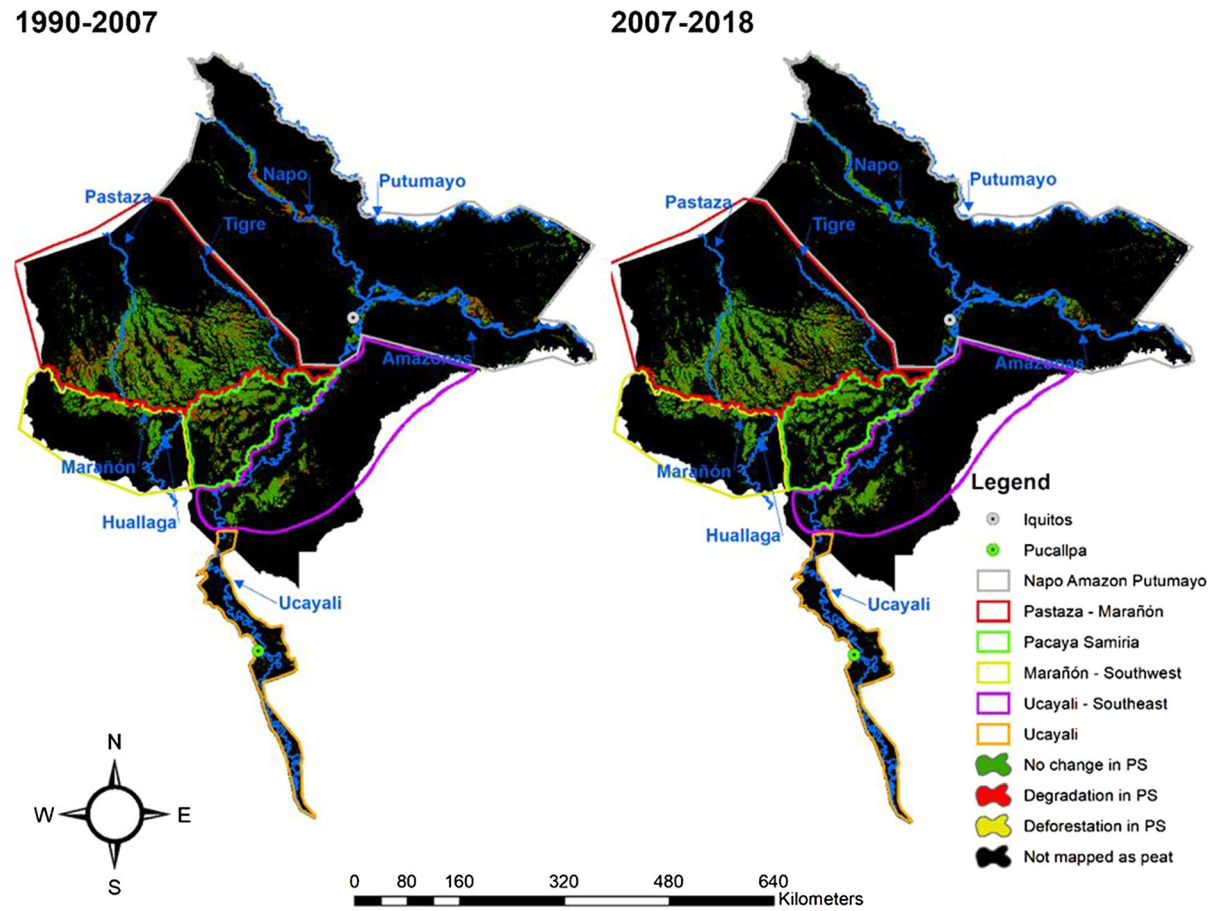

Fig. 9 Spatial distribution of palm swamp (PS) degradation and deforestation on peat for the periods 1990–2007 and 2007–2018

it being degraded (85%). The estimated carbon emissions from disturbance amounted to 31.5 ± 3.5 Tg C over 1990–2018, with the rate of degradation increasing from 15,424 ± 391 ha per year in 1990–2007 to 17,653 ± 456 ha per year in 2007–2018, and the rate of deforestation more than doubling from 1933 ± 34 ha per year to 4197 ± 97 ha per year. Geographically, the Pastaza-Marañón area saw a 32% increase in the rate of degradation, while the Pacaya-Samiria National Reserve saw a drop of 37% (Fig. 9). The rate of deforestation increased everywhere except for the Ucayali area. The emissions over 1990–2018 were more than double Peru's carbon emissions in 2021 from burning fossil fuels and industry, highlighting the importance of accounting for emissions resulting from peatland disturbance.

Australia

Peatlands cover approximately 2.3 Mha in Australia, with Tasmania accounting for almost 80% of them. Peatlands on the mainland are not extensive, and therefore, they do not appear on soil maps, making it difficult to estimate their exact extent. Based on the Australian Soil Classification system, mainland Australia has an estimated 150,000 hectares of Organosols. This number increases to around 482,000 hectares when including peat areas from various mapping sources and scales.

Most of the alpine and sub-alpine peatlands in Australia are protected in national parks or state forests. Despite this protection, fires on peatlands are frequent, and the catastrophic bushfires of 2019–2020 burned 17 million hectares of land across the

continent. In response, the Australian Government commissioned an independent ecological assessment to determine the sensitivity and exposure of vulnerable ecosystems to multiple fire-related threats. In Tasmania, there is an effort to create high-resolution digital soil maps, and peatland maps have been created to aid fire management and improve understanding of the extent of the organic soil resource.

A Digital Soil Mapping (DSM) approach was used to predict peatland areas using new and existing soil site data, intersected with a range of environmental spatial datasets. For the Tasmanian mapping, organic soils were defined based on their burn risk with > 12% SOC and depth > 5 cm. The mapping effort combined existing and newly captured site data, along with expert desktop inputs indicating presence or absence of peat soils. These over 13,000 observations were combined with remote sensing covariates via a machine learning model. The resulting maps (Fig. 10) are spatial layers at 30 m resolution showing the extent and likelihood of organic soil, site drainage, organic layer depth, organic C content and degree of humification. The DSM estimated peat soils cover about 1.3 Mha in Tasmania, with 90% in conservation and natural environment areas. A further 0.5 Mha of rainforest area was modelled to have peat and organic soils (or surface litter accumulations), however these estimates are low confidence due to lack of site data. The model shows the importance of detailed vegetation data for accurate prediction of peat occurrence since many areas are remote and difficult to reach (Kidd et al. 2021).

During the 2021–2022 fire season, the peat maps were used in fire management efforts, and some areas were identified for improvement. The maps were used to design plan to prioritise areas for infra-red camera scanning and to protect important organic stores in high fire danger zones.

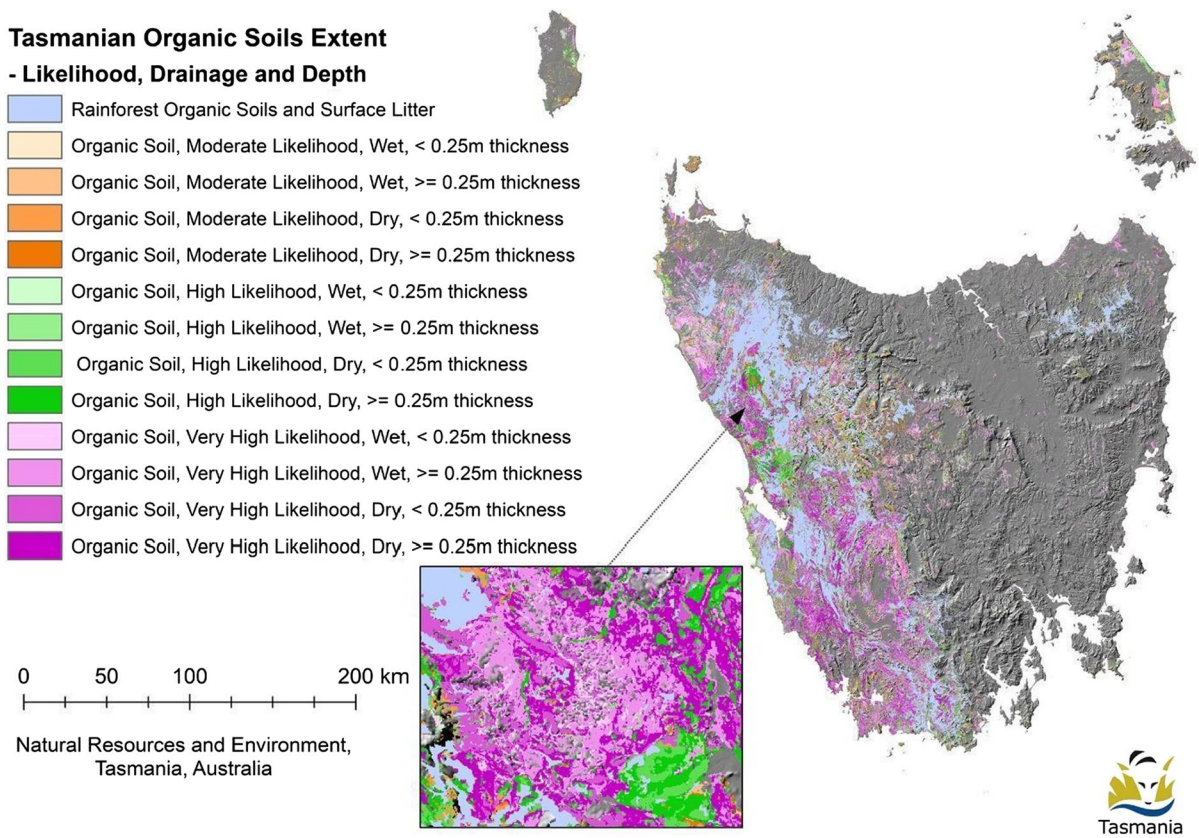

Fig. 10 The likelihood of organic soil and its drainage and thickness in Tasmania, Australia

Table 1 Summary of peatland and mapping characteristics (*SOC* soil organic carbon, *OM* organic matter)

Country	Primary peat or peatland definition	Map and units	Scale	National coverage (all area types)	Year created and data sources
Norway	Areas with peatland vegetation and at least 30 cm of peat	AR50: Individual peatland (Polygons)	1:50,000	100%	2009, based on field surveys under the tree line and combination of topographic maps and satellite images over the tree line
		AR5: Individual peatland (Polygons)	1:1000	59%	1960–1990, Field surveys, below tree line
Finland	Areas with peatland vegetation and at least 30 cm of peat	Topographic Database by National Land Survey of Finland: Individual peatland polygons	1:1000	100%	Constantly updated, based on aerial photographs, scanning data and data provided by other data providers
Denmark	Areas with at least 6% SOC	SINKS soil database			2010-current, soil inventories
	Areas with at least 12% SOC and 30 cm peat thickness	wetlands, regional average (Polygon)	1:50,000	100%	2010, soil inventories
	All wetland areas	centallav, regional average (Polygon)	1:20,000	100%	1915–2009, delineated from topographical maps
	Larger peat areas with at least 30 cm thickness	moser, Individual peatland (Polygon)	1:20,000	approx. 50%	1919–1942, surveys
UK	Areas with at least 50 cm depth of > 35% SOC (Scotland); or 40 cm of > 20% (N Ireland) or 40 cm of > 50% OM (England and Wales)	Individual peatland (Polygon)	Variably by country	100%	Pre-1960s to current. Soil (reconnaissance) surveys plus expert judgment based on field surveys of vegetation and degradation features for derivation of polygons, and more recently, digital soil mapping with remote sensing interpretation. Additional validation data from various soil surveys
Austria	All areas with at least 30 cm of peat. Peat is material with at least 35% OM	Regional average (Polygon)		ca 50%	1960s- current, soil survey
Ireland	Consisting of at least 30% of OM over a depth of at least 45 cm on undrained land and 30 cm deep on drained land on at least 1 ha; the depth requirement does not apply if the peat layer is over bedrock	Peat coverage (Raster)	Resolution 300 m	100% (Overall accuracy 88%)	2009 (based on data from 1980s to 2009), integration of soil, land cover and field survey

Table 1 (continued)

Country	Primary peat or peatland definition	Map and units	Scale	National coverage (all area types)	Year created and data sources
Australia	Areas with > 12% SOC and peat thickness at least 5 cm	Peat coverage (Raster)	Resolution 30 m	Detail in Tasmania or 80% of peatlands (Overall accuracy 70%)	2021, integration of soil and survey data with remote sensing covariates
Canada	Areas with > 17% SOC (30% OM) and a peat thickness at least 40 cm (if the surface is mesic of humic) or 60 cm (if the surface is fibric)	Individual peatland (Polygon)	Varies from a province/territory to another	Less than 40% if all provinces and territories are included	2002-present, from aerial photography, satellite imagery and field survey

Discussion

The collection of case studies presented here demonstrate the importance of peatland mapping for ecosystem functions and services, including agriculture, carbon stock, biodiversity, fire management and GHG emissions.

Table 1 presents an overview of the various methodologies used to map peatlands in several case study countries. A notable observation is that the definition of peat soil and peatland differs across the countries examined in this study, which is a recurring theme in the literature (Lourenco et al. 2022). In addition, most of the definitions of peatland (Table 1) are a mapping or operational definition according to the national land survey. For example, in Finland and Norway, peatlands are defined as areas with at least 30 cm of peat and the presence of peatland vegetation. In Finland, this definition is applied for the 97% of peatlands excluding the ones under agricultural use. For organic soils in agricultural use organic matter content should be > 35% and C on mass basis > 20%. Denmark uses a similar definition in the mapping layer moser, but it additionally accounts for peatland areas with at least 6% SOC in the SINKs soil database and organic soils that are at least 12% SOC down to 30 cm depth. This criterion of soil organic matter (SOM) content is also incorporated in the definitions of the UK, Austria, Ireland, and Australia. The thickness and percentage SOM requirements vary across the UK, ranging from 50 cm depth of > 35% SOC in Scotland, to 40 cm of > 20% in Northern Ireland, and 40 cm of > 50% based on Loss on Ignition (or SOM) in England and Wales. In Ireland, the peatland definition specifies that there must be at least 30% OM to a depth of at least 45 cm, but the definition is further differentiated with a shallower depth requirement of 30 cm on drained land (Hammond 1981). Furthermore, peatlands in Ireland are defined as a geographical area where peat occurs and should have a minimum spatial extent of 1 ha (Connolly and Holden 2009). In Australia, the definition of peatland is the most lenient, with a requirement of > 12% SOC to a depth of > 5 cm. Whereas in Canada, the thickness criteria are based on the degree of humification.

The majority of countries populate their maps through a combination of soil surveys, classification of topographical maps and delineation of remote sensing images. To improve mapping, several

countries (e.g., Ireland, UK, Norway, Finland) are using airborne geophysical data to assist in delineating peatlands. However, national coverage of peatland maps varies by country with the majority providing 100% coverage but at different resolutions and with different levels of detail. Austria, Denmark and Norway have detailed maps of peatland extent covering approximately 50% of the country. Both Denmark and Norway also offer additional mapping resources that increase that coverage. Norway, for example, provides 100% coverage of peatland extent but at a lower resolution and with greater uncertainty. The extent of peatland condition information varies considerably with the majority providing some information about peat depth/thickness and only a limited number also providing humification degree, C content, and vegetation cover.

The use of different definitions for peatlands across various regions has resulted in discrepancies in the reported coverage of peatland areas. For example, in Norway, peatland is defined separately from organic soils, which may explain why their peatland area appears smaller than in other European countries, despite having high levels of organic matter in their soils. Additionally, forested peatland areas are often classified as forest rather than peatland and similarly with grasslands, and only potentially productive lowlands are included in peatland maps, reflecting historic agricultural policy. There are specific challenges in mapping peatlands, such as the differences in mapping quality in agricultural and forested land and difficulties in using remote sensing in forested areas. If countries are to meet their climate goals however, peatland mapping improvements need to be undertaken to inform their protection and urgent restoration. Each country needs to clearly define what they mean by peatlands, starting with the definition provided by international convention (e.g. Histosols according to the World Reference Base).

Most countries are now employing remote sensing and machine learning methods to improve the national mapping of peat extent. While there are inconsistencies in the definition of critical thickness, most countries define peatlands as areas with a certain amount of SOC content. A possible future effort to harmonise these maps would involve accurately mapping SOC at various depth intervals and delineate peatlands based on internationally agreed SOC stock values. Current continental (Ballabio et al. 2016) and global soil maps (e.g. Poggio et al. 2021; Padarian et al. 2022) do not explicitly consider peatland areas. However, a significant challenge remains in accurately mapping peat thickness and carbon stock.

Monitoring of peatland conditions

Rationale for the assessment of peatland conditions

The long-term drainage of peatlands for many centuries led to non-reversible changes in their physico-chemical soil characteristics (Zak et al. 2008; Price et al. 2016; Leifeld et al. 2020; Wang et al. 2020; Fluet-Chouinard et al. 2023). In Europe during the 1960s, drainage was intensified to convert peatlands to grassland and land for other arable crop production or to improve tree growth in forested peatlands and to extract peat for fuel or horticultural uses. In many

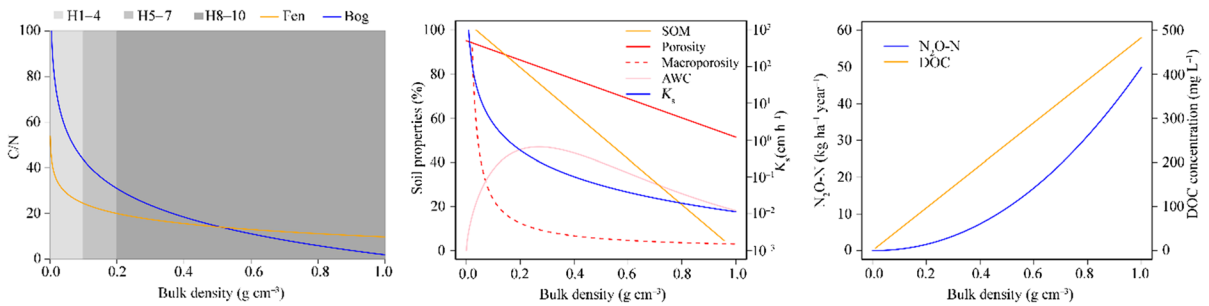

Fig. 11 Peat degradation due to drainage for land use and accompanied mineralisation processes led to increase of bulk density, degree of humification (H1-10, von Post et al. 1922) and other related "soil degradation parameters" (*SOM* soil organic matter, *AWC* available water capacity, K_s saturated hydraulic conductivity) as well as nitrous oxide (N_2O) fluxes and dissolved organic carbon (DOC) concentrations in soil water. Data from Liu and Lennartz (2019) and Liu et al. (2019)

cases, drainage practices lowered the groundwater table by more than 1 m, causing severe peat soil degradation (Holden et al. 2004). Currently, drained peatlands constitute approximately 12% of the total global peatland, with Europe accounting for around 50% of this proportion. In certain countries, the percentage of drained peatlands exceeds 90% of the total peatland area. (e.g., Denmark, Germany, Ireland, Luxembourg, the Netherlands and Portugal; Tanneberger et al. 2021; Fluet-Chouinard et al. 2023).

Peatland drainage has numerous consequences on peat soil properties, as depicted in Fig. 11, and these impacts significantly undermine the functioning of the ecosystems (Price et al. 2016). The most obvious effect of lowering water tables for land use is the aeration and subsequent mineralisation of the drained soil layer, which was built up over centuries, turning peatlands from sinks into sources of carbon and nutrients.

In carbon budget terms, it has been shown that a simple proxy, the mean effective annual water table depth, that is, the water table depth within the layer of peat, can be used as a robust predictor of mean net carbon dioxide exchange and methane emissions over multiannual timescales (Couwenberg et al. 2011; Evans et al. 2021; Ma et al. 2022; Prananto et al. 2020; Turetsky et al. 2014; Tiemeyer et al. 2020). The understanding of these effects, along with model projections indicating additional drying in several Northern hemisphere peatland regions due to climate change (Qiu et al. 2022), has influenced a policy shift aimed at preventing further degradation. This shift also promotes the restoration of wet conditions or the adoption of paludiculture approaches for drained peatlands (e.g., Strack et al. 2022).

Furthermore, the lowering of water levels in peatlands leads to peat subsidence and compaction, resulting in reduced soil porosity, hydraulic conductivity, and enhanced the degree of humification in the drained peat layers (e.g., Liu et al. 2019). These changes can be challenging to reverse solely through rewetting efforts. Indeed, layers of highly humified peat, assumed to have formed during drought phases are common in peatlands and have the capacity to incur a 'memory effect' on future hydrological behaviour of the peatland (Belyea and Baird 2006). Recent advances in interferometric SAR application are thought to be able to assess an element of such feedback, via the monitoring of the temporal rise and fall of the peatland surface. Section "Field scale monitoring" and "Regional monitoring" discuss the current development of such methods to monitor water table depth and other ecohydrological proxies.

Drainage also increases the amplitude of usual water table fluctuations, consequently increasing fungal proliferation and accelerating organic matter decomposition (Kim et al. 2021). At individual site-level, however, water table depth relationships derived from global data is not always applicable, for example on sites where periodic inundation causes methane fluxes to be much higher than expected by global relationships (e.g., Tiemeyer et al. 2020) or where vegetation or water quality characteristics are more important (e.g., Zak et al. 2021). Mapping of vegetation as a proxy for various processes in carbon cycling and to delineate different peatland types is relatively well established across multiple scales and examples are given in subsequent sections.

Other major terms in the net ecosystem carbon budgets are losses of dissolved and particulate organic carbon, which can be particularly high from eroding or other areas devoid of vegetation. While simple proxies for such loss terms are not established at present, mapping of man made drainage networks and erosion features is advancing rapidly. We give examples of the state of development at field and regional scale Sects. "Field scale monitoring" and "Regional monitoring".

The oxidation of peat during long-term drainage also leads to enrichment of phosphorus (P), iron (Fe) and aluminum (Al) with decreasing molar ratios of C:P and C:N in upper soil layers (Zak and Gelbrecht 2007). Concurrently, refractory organic-bound P is transformed into more labile and mobile inorganic P forms. Such P can become sorbed onto redox-sensitive Fe(III) hydroxides, formed by the oxidation of iron sulfides, or on other reactive surfaces from metal oxides (Zak et al. 2008). These processes explain the elevated P mobilisation potential in highly decomposed peat compared to slightly decomposed peat of deeper un-drained soil layers of drained peatlands and/or natural peatlands. Furthermore, both for bog and fen peatlands, polyphenolic compounds, specifically condensed tannins, acting as a constraint on organic matter decomposition under non-drained conditions, are lost after long-term drainage (Freeman et al. 2001; Zak et al. 2019). The recovery of these compounds is strongly linked to the re-establishment of peat-forming vegetation, which can be retarded

upon peatland rewetting (Kreyling et al. 2021; Temmink et al. 2022). The enrichment of nutrients, oxidised substances and the lack of condensed tannins foster the microbial decomposition processes in the peat soil under both aerobic drained, anaerobic rewetted conditions and partly also under natural conditions (e.g. increased nutrient loading). This is discussed in Sect. "Caveats and limitations".

A final point in relation to peatland monitoring must address nitrous oxide (N_2O) emissions, which can be high from drained nutrient-rich peatlands and/or those under agricultural use. Direct monitoring for nitrous oxide fluxes remain limited, but some proxies proved to be promising, such as water table height, water filled pore space (wfps) (Hergoualc'h et al. 2020), degree of humification, bulk density (e.g., Liu et al. 2020a, b) or C/N ratio (e.g., Yao et al. 2022). Liu et al. (2019) highlighted the urgent need to address this issue.

The following sections review indicators and approaches for monitoring peat conditions from the profile up to the global scale with the aim to identify key parameters that can be used to characterise peatland functions: GHG emission mitigation, C storage, water and nutrient storage and cycling, and biodiversity habitat.

Monitoring at profile scale: peat soil indicators

There is a need for simple and accurate parameters that can quickly factor in peat degradation stages when assessing GHG emissions and nutrient fluxes from peatlands or the peat degradation state. Some easily measured peat indicators are outlined below.

Degree of humification

A long-term established simple method for determining the degree of humification is the von Post method, which enables the differentiation of 10 humification degrees (von Post et al. 1922). Long-term drainage turns slightly decomposed peat soils into highly decomposed peat or completely humified peat. Because peat near the soil surface is most strongly affected by drainage and desiccation, a characteristic vertical gradient from highly to slightly humified peat is formed both in drained bogs and fens (Schindler et al. 2003). The degree of peat decomposition reflects the quantitative ratio of dark amorphous decomposed matter to non-decomposed materials (Drzymulska 2016).

This simple test of the degree of peat decomposition was found to be a suitable proxy for assessing the risk of high mobilisation of P, dissolved organic carbon (DOC) and ammonium (NH_4^+) in rewetted peatlands (Zak and Gelbrecht 2007). Thus, high mobilisation of P, DOC and NH_4^+ is only likely if the upper soil layers consist of highly decomposed peat, while underlying less decomposed peat is only a weak source of these substances (Zak et al. 2018). There have been attempts to correlate the degree of humification with distinct chemical properties but with limited success (Biester et al. 2014; Drzymulska 2016).

Physical proxies for humification, such as peat ash content and bulk density, have been intensively tested as they are easy to determine and could enable more extensive inventories and faster results (e.g., reviewed by Zaccone et al. 2018). Peat carbon to ash quotient has been used as an indicator for quantifying the cumulative post-drainage impacts on the C store (Grønlund et al. 2008). The rationale is that surface peat C losses are induced by decomposition following drainage and cultivation, whereas the mineral (ash) content is not as easily lost as carbon and its concentration will thus increase (Laiho and Pearson 2016). It has been suggested that this method may be more suitable for bogs where the input of minerals is solely atmospheric, whereas in minerotrophic fens inputs from ground or surface water are likely to influence the ash content (Krüger et al. 2015). The method has been applied in peat soils under agricultural use (Grønlund et al. 2008). In forested peatlands, Krüger et al. (2015) found small non-significant differences in ash content between undrained and drained sites when comparing nearby pairs of sites in the same peatland complex.

Further methodological uncertainty is introduced when comparing undrained and drained peatland profiles due to peat subsidence and compaction following drainage. Compaction is expected to be greatest in the topmost layers and to decrease downwards. On the other hand, if the site is drained for forestry, more litter with lower density and ash content is accumulated on top of the peat due to increased tree growth (Laiho and Pearson 2016). As a rule, the ash or carbon method is better applicable in severely degraded bogs under intensive agricultural use.

Dry bulk density

Soil dry bulk density is an important soil parameter in peatland hydrology as it is a controlling factor for the water flux in peat soils (Liu and Lennartz 2019). However, bulk density can also be used as an indicator of peat decomposition. The gradual increase of soil bulk density originates from peatland subsidence along with peat decomposition and degradation processes. Peatland subsidence is caused by soil shrinkage above water table depth, soil compaction below water table depth and soil carbon mineralisation (Kennedy and Price 2004). Peatland subsidence substantially reduces soil porosity and macroporosity (Liu et al. 2020a). At the same time, as organic particles are depleted, mineral substrate is concentrated, and the soil bulk density therefore increases. During the peat degradation processes, only carbon mineralisation is directly linked to carbon loss. However, it should be noted that soil shrinkage and compaction increase soil water retention (Liu and Lennartz 2019), which may indirectly affect the carbon and nitrogen mineralisation rate.

Previous studies have shown that the bulk density of peat is an important parameter that can be used to estimate hydrophysical properties (e.g., soil organic matter content, saturated hydraulic conductivity; Fig. 6; Liu et al. 2020a; Morris et al. 2019) and biogeochemical properties (e.g., heterotrophic carbon dioxide emissions; Ojanen et al. 2010, nitrous oxide emissions, dissolved organic carbon content; Liu et al. 2019). Compared with other indicators of peat decomposition (e.g., von Post and C:N), soil bulk density is more sensitive to carbon loss for highly degraded peat soils (bulk density > 0.2 g cm^{-3}; Fig. 12), where relatively constant values of the degree of peat decomposition and C/N ratios are observed (Fig. 13; Liu et al. 2019).

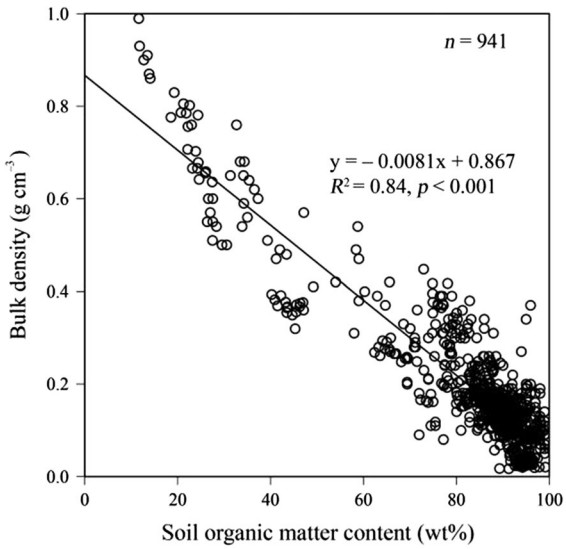

Fig. 12 Soil organic matter content of peat soils as a function of bulk density. The data comes from Liu et al. (2020b)

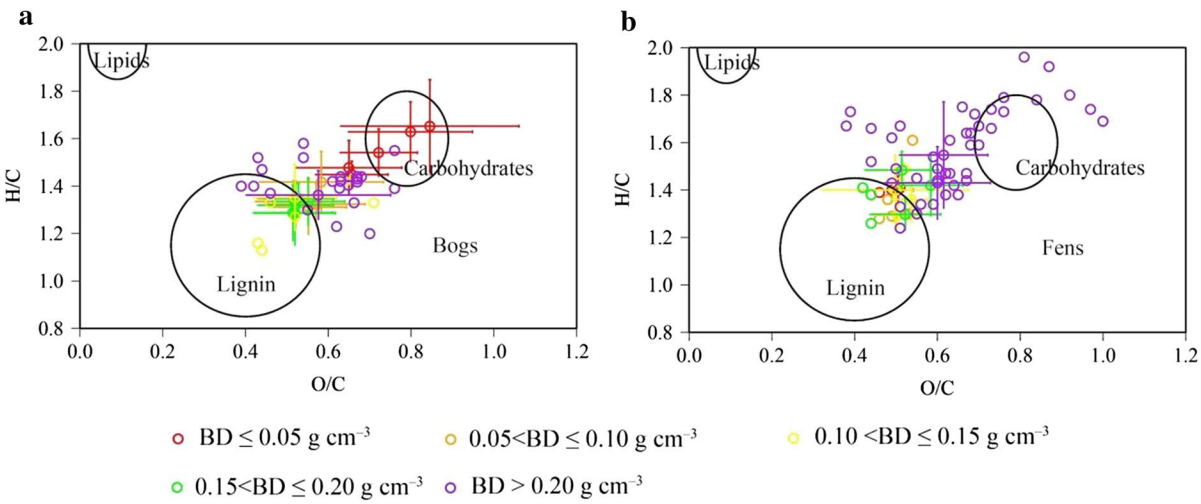

Fig. 13 The atomic oxygen-to-carbon (O/C) and hydrogen-to-carbon (H/C) ratios of differently degraded bogs (**a**) and fens (**b**). The figure is adapted from Liu et al. (2019) with permission

After peatland rewetting, the topsoil bulk density may decrease due to new peat accumulation or secondary peat formation (McCarter and Price 2015). However, the bulk density of the old peat may remain high, making the rewetted peatland a new ecosystem, e.g. eutrophic shallow lakes are often formed on top of the degraded peat soil (Kreyling et al. 2021). The soil bulk density of peat is not only related to the soil organic matter content, it also reflects the gradient of carbon quality along with the soil degradation processes (Fig. 13). For bogs, easily degradable compounds (e.g., carbohydrate-like materials) are accumulated during the peat formation process, and these compounds disappear during peat decomposition. Thus, highly degraded bogs contain large amounts of recalcitrant compounds (lignin-like materials). However, highly degraded fens still contain substantial amounts of easily degradable compounds, possibly because of inputs of fresh plant litter to the topsoil (Bader et al. 2018).

Stoichiometry

The stoichiometric ratios of carbon (C), nitrogen (N) and phosphorus (P) are crucial for understanding the nutrient limitation, composition and cycling processes in peatlands (Wang et al. 2015; Moore et al. 2011). Thus, for instance, the C:N ratio has been proposed to indicate peat decomposition (Krüger et al. 2015). Comparing peat C and N from mostly intact northern peatlands reveals that agriculture and, to a lesser extent, forestry induced a progressed state of soil degradation (Leifeld et al. 2020). For natural, less decomposed peat soils, the values of C:N ratios were found to range between 20 and 98 (Zak et al. 2010). Peat decomposition leads to carbon mineralisation and relative enrichment of N, and the C:N ratio accordingly decreases during the peat decomposition and degradation processes. For highly degraded peat soils, the C:N ratio can be as low as 10 (Liu et al. 2019; Petersen et al. 2020). A significant amount of organic carbon is lost during peat decomposition, while phosphorus tends to remain relatively immobile (Zak and Gelbrecht 2007), and C:P may therefore also reflect the peat decomposition stages. However, compared with other indicators (e.g., von Post degree of humification, C:N, bulk density), the C:P ratio is less sensitive to the early stages of peat decomposition where significant amounts of P may be lost through plant uptake. For bogs, the C:P ratio has been shown to both increase (Wang et al. 2015) and decrease (Moore et al. 2011) during the peat decomposition process.

Peatland rewetting induces anaerobic conditions where the formerly accumulated P may be mobilised. The P mobilisation is closely linked to the redox-sensitive iron or Fe(III) compounds (Zak et al. 2008). A crucial molar ratio of Fe:P of 10 was observed in a previous study, below which there would be a high risk of P export to adjacent lakes or rivers in peatland catchments (Zak et al. 2010). Therefore, monitoring these soil properties to elaborate a water eutrophication risk map before peatland rewetting is recommended. On the other hand, with a lower Fe:P ratio, the P availability to plants will be diminished faster, so rewetting of Fe-poor fens will foster the restoration of endangered fen species more quickly than in Fe-rich fens (Emsens et al. 2017).

Infrared spectral signatures

Spectral signatures from the near-infrared (NIR, 700–2500 nm) and mid-infrared (MIR, 2500–25,000 nm) regions have been widely used to characterise soil properties (Ng et al. 2022). However, the application of infrared spectroscopy to peat soils is still minimal. NIR spectroscopy has been successfully used to predict peat C and N content (de Sousa Mendes et al. 2022) as well as peat type classification and humification degree (Granlund et al. 2021). Artz et al. (2008) evaluated the use of Fourier-transform mid-infrared spectra to predict the organic matter composition, including C:N ratios and carbohydrate signatures. This rapid assessment can be used as an initial screening tool to trace organic matter decomposition and thus to evaluate the present and future organic matter composition of peat during restoration efforts (Reuter et al. 2020).

Field scale monitoring

Peatland monitoring on the field scale gathers information on the condition, function, and changes of peatlands over time. The spatial extent can range from small areas of one hectare to vast expanses spanning thousands of hectares, with measurement resolutions varying from as fine as 1 m to as coarse as 100 m. Field-scale monitoring provides data on parameters such as water table depth, peat thickness, C storage,

vegetation cover, GHG emissions, nutrient cycling, and biodiversity. This information can help identify early warning signs of degradation or identify opportunities for restoration interventions.

The term proximal sensors refers to sensors that operate in close proximity to the ground's surface, in contrast to remote sensing techniques that measure reflected or emitted radiation from a distance. Proximal geophysical sensors offer high-resolution mapping and characterization of soil properties with penetration depths and resolution from less than a meter to tens of meters (Garré et al. 2022; Minasny et al. 2019). Widely utilised in geophysical surveys, many proximal sensors have been tested for their ability to measure peat thickness, such as electrical resistivity tomography (ERT), electromagnetic induction (EMI) and ground penetrating radar (GPR). These sensors primarily rely on peat's high organic matter containing large porosity and water content and thus low electrical conductivity (Comas and Slater 2004; Theimer et al. 1994).

Gamma radiometric sensors, which were designed to detect the natural radioelements of soil and geological materials, become useful for mapping peatland boundaries and intra-peat variation in water content. The gamma signal of peat is distinct due to its high organic matter, water content and low density. Mixed results were obtained with a few studies showcasing its ability to map peat thickness (Gatis et al. 2019; Keaney et al. 2013; Marchant 2021) while others argue that the technique is mainly suitable to demarcate the peatland boundaries or discern intra-peat variation in water content as most of the signal attenuates (Beamish 2013; O'Leary et al. 2022, 2023). Modern portable gamma radiometric sensors allow for both proximal and remote sensing by using either airplanes and unmanned aerial or all-terrain vehicles and offer the possibility of field assessment

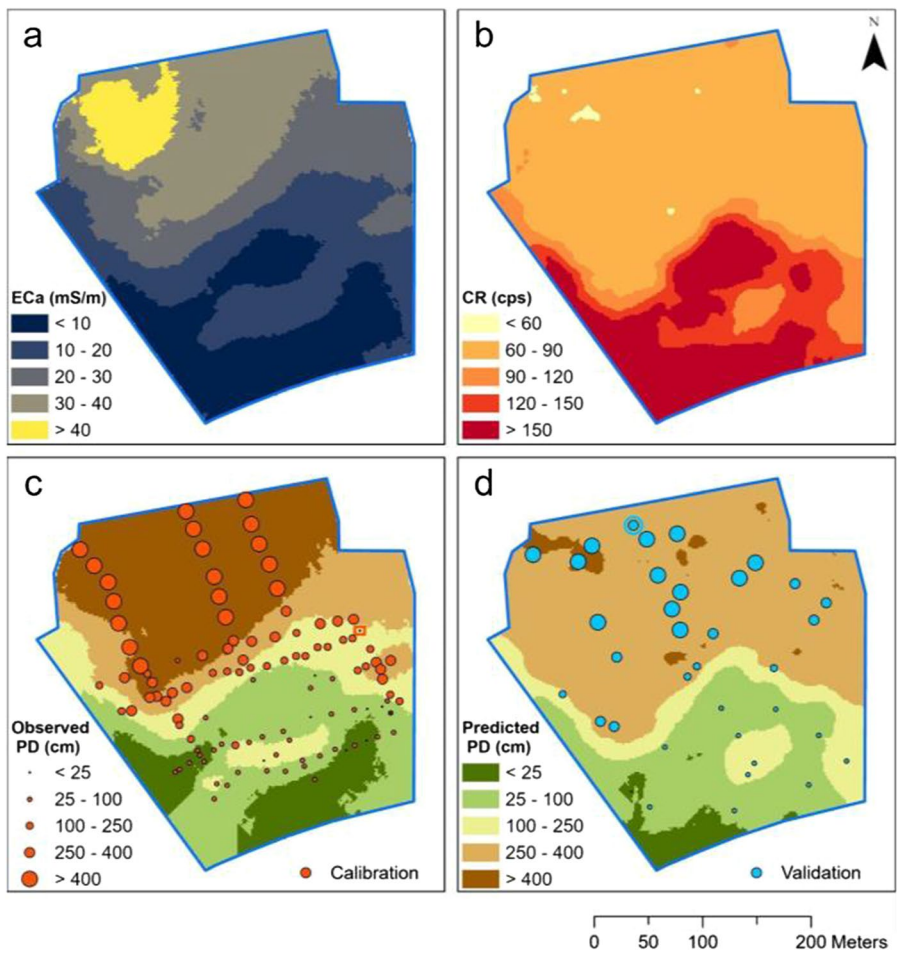

Fig. 14 Maps showing (**a**) apparent electrical conductivity measured by the HCP4m measuring channel of DUALEM-421s (DUALEM Inc., Ontario, Canada) instrument, (**b**) gamma ray count rates measured by Medusa MS-1000 (Medusa Radiometrics BV, Groningen, Netherlands) instrument. Predicted peat thickness (PD) maps using linear regression modeling based on (**c**) apparent electrical conductivity overlain by calibration locations and (**d**) count rates overlain by validation locations. The manual probing measurements that are unusually low are highlighted and considered as outliers. Sub-figures (**a**) and (**c**) are adapted from Beucher et al. (2020)

under various conditions (van der Veeke et al. 2021; O'Leary et al. 2022).

Figure 14 shows an example from a 10 ha fen peatland in Denmark with a high gradient (0–730 cm) in peat thickness from south to north (shallow to deep peat). Here, the mineral soil to the south is predominantly sandy and a sandy hill is located in the south-central region. Both gamma radiometric and EMI surveys respond to peat thickness. The more conductive areas in the north are characterised by low radiometric counts. However, gamma radiometrics was inferior to EMI in capturing variability in areas with thicker peat deposits in the north. This is clearly reflected in the prediction maps as areas with deeper peat thickness were severely under-predicted with the gamma-ray sensor leading to poor accuracy ($R^2 = 0.55$) compared to the EMI sensor ($R^2 = 0.86$).

However, it should be acknowledged that both sensors have their own capabilities and limitations, and the gamma sensor is still suitable to delineate shallow peat that is crucial to assess GHG emissions (Evans et al. 2021; Tiemeyer et al. 2020). For example, in Denmark, efforts are underway to develop a suite of unmanned aerial vehicle borne sensors (EMI, GPR, and GR) to facilitate faster data acquisition with minimal disturbance to the pristine areas. These detailed peatland maps can be used to monitor GHG hotspots. Most studies explored temporal variability of N_2O yet studies have shown that N_2O and CH_4 emissions can significantly vary spatially (McDaniel et al. 2017).

In addition, UAV-based surveys have proven to be highly effective in monitoring changes in local-scale conditions, as demonstrated by studies such as Scholefield et al. (2019), Sterk (2022), and Glendell et al. (2017). With the increasing availability of high-resolution aerial photography and satellite imagery, the detection of small landscape features, including erosion and drainage features, can be more accurately mapped as an alternative to more expensive LiDAR-based mapping (Dadap et al. 2021; Connolly and Holden 2017). Robb et al. (2023) provided a comprehensive review of this approach.

Certain peatlands exhibit a more intricate soil profile, characterized by the presence of a limnic layer situated between the peaty and mineral components. This layer consists of an impermeable sedimentary material predominantly composed of residues from aquatic plants or animals. In Canada, three types of limnic layers are found: coprogenous earth, diatomaceous earth, and marl (Soil Classification Working Group [SCWG] 1998). In European soil classification systems, it is called gyttja (Larsson 1990; Berglund 1996; Schulz et al. 2019), and there are other types defined by the composition of the material. The depth and thickness of this limnic layer can vary significantly at the field-scale, making it almost impossible to predict using only remote sensing data (Deragon et al. 2023). Limnic layers pose an additional challenge: they are often associated with higher salinity levels, which can hinder the use of some proximal sensors like GPR as its signal dissipates. Point-based probes and proximal sensors could provide the accuracy needed to detect and discriminate peaty, limnic, and mineral layers. Distinguishing between peat and limnic layers can provide additional information that helps better management of peatlands (e.g., soil conservation, agricultural use, C stock mapping, GHG emissions, etc.).

Proximal sensors speed up modern soil surveys by gathering large quantities of data rapidly, but they still rely on manual sampling sites to construct and validate predictive models. This step is labour and time intensive. Point-based probes such as time-domain reflectometry (TDR) or soil penetrometers could be viable alternatives in shallow soils if they could be automated and geo-referenced. Subsequently, these measurements can be correlated with those of proximal sensors (such as gamma radiometric and EMI) to generate detailed maps of the peat thickness.

TDR probes can assess soil volumetric water content and salinity in situ (Dalton et al. 1984). They have a relatively small sample volume, which enables them to provide precise measurements of volumetric water content if the soil salinity is low (Ward et al. 1994). An experiment was conducted by measuring the electrical conductivity and dielectric constant (Ka, measured using TDR) of a peat profile in Canada from the surface to a depth of 104 cm. The results showed a clear distinction in electrical behavior for mineral, peats, and limnic materials (Fig. 15). The soils' dielectric properties (Ka), although related to the water content, could be used to discriminate between the three soil materials. For a practical measurement of the depth of different peat materials, a penetrometer was used. Mineral layers exhibited high penetration resistance, while coprogenous layers with their gelatinous nature offered low resistance, and peaty layers fell somewhere in between. Thus, a combination of

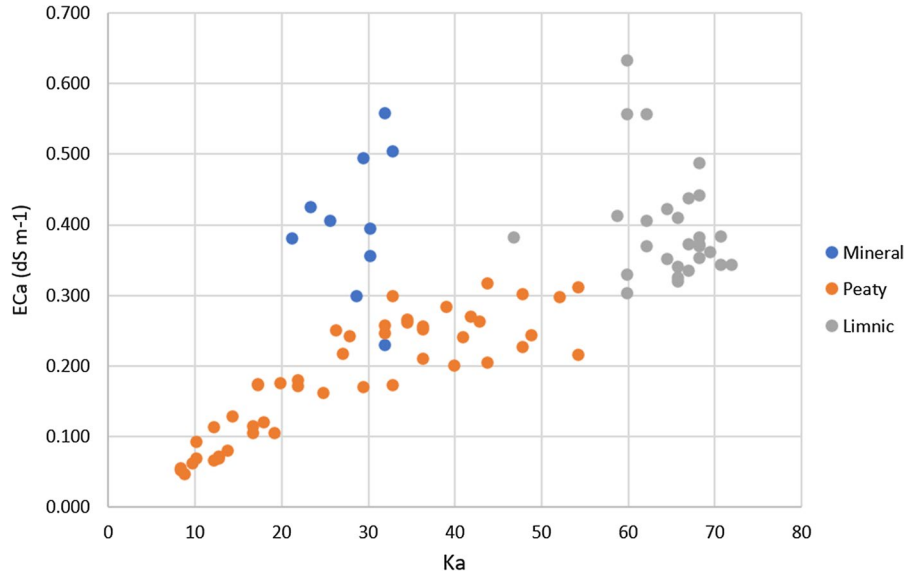

Fig. 15 Electrical conductivity (ECa) and apparent dielectric permittivity (Ka) of peat materials measured with a Tektronix 1502B grouped by three soil types found in the soil profiles: mineral, limnic and peaty layers. (Credit: Sébastien St-Onge, reproduced with permission)

a penetrometer and TDR probe could provide point observations of peat thickness and stratigraphy within the first meter of soil.

Regional monitoring

Remote-sensing techniques are effective in monitoring peatland conditions, especially areas under intense human pressures over large spatial extents, such as drainage patterns, vegetation inundation extent, surface moisture content, and relative water table position. Passive remote sensing detects electromagnetic radiation emitted or reflected by Earth's surface or atmosphere. It includes optical sensors (e.g., visible and NIR range) and can detect changes in absorbance of peats and vegetation over landscapes, while thermal infrared (TIR) measures surface temperatures and infers soil water content. Airborne radiometrics that detect naturally occurring emissions of minerals can also be used to detect peat (O'Leary et al. 2022). Active remote sensing emits electromagnetic energy, including microwaves and LiDAR, towards the surface and measures the amount reflected to the sensor. Airborne electromagnetic induction method can detect the volume of peats over large areas (Silvestri et al. 2019). Microwave imaging such as synthetic aperture radar (SAR) can detect ground motion and changes in surface texture and vegetation height. It can also detect land cover, vegetation structure, and soil water content through backscatter detection. LiDAR measures surface structural changes (Lees et al. 2018).

These sensors can be used to monitor various aspects of peatland hydrology. However, the types of imagery and products are not universal and require regional specific calibration. For example, MODIS data have a spatial resolution of 250 m to 1 km and cover the earth's surface every 1–2 days. Landsat satellites cover the Earth every 8–16 days and have a spatial resolution of 30 m. Sentinel-2 satellites, with a return interval of every 5 days, have a multispectral imager with a resolution of up to 10 m.

Airborne gamma radiometrics and electromagnetic induction have been proven to be effective proxies for large scale peat and peat thickness detection. Recent advances in airborne electromagnetic induction have increased the ability to obtain measurements with high vertical resolution at shallow depths (Silvestri et al. 2019; Siemon et al. 2020). Helicopter carrying the electromagnetic induction system can fly an altitude of 25–65 m above the ground, with flight lines at 200 m to 1 km. The electrical conductivity data through inverse modelling can resolve peat volume at a high accuracy. However the cost of such surveys may restrict the application for baseline monitoring.

Interferometric synthetic aperture radar (InSAR) has been tested to detect the surface motion of peatlands. Well-maintained peatlands have the ability to self-regulate the depth of the water table through

a process known as "bog breathing". However, degraded peatland surfaces tend to be stiffer and can experience surface oscillations, peat slides, and bog bursts (Alshammari et al. 2020, 2018; Bradley et al. 2022; Marshall et al. 2022). InSAR has been utilised to monitor tropical peatland subsidence in areas with contrasting land use change (Umarhadi et al. 2021) and detect peatland landslides in Ireland (Islam et al. 2022).

The SAR backscatter can also infer water table depth and soil moisture dynamics and be used to model carbon dioxide and methane emissions. Such regression analysis has been tested in a controlled environment (Toca et al. 2022) and in the setting of a landscape scale restoration experiment (Toca et al. 2023). These remote sensing and modeling approaches can supplement the growing network of eddy covariance-based observations of GHG emissions.

There is a potential of using high-resolution optical remote sensing methods to estimate carbon fluxes in peatlands (Lees et al. 2018; Lees et al. 2021). A combination of visible and NIR wavelengths could model gross primary production (GPP) in peatlands with temperature and water content modifiers. However, modelling respiration in peatlands is still challenging due to the sensitivity to temperature, productivity/biomass, and soil water content. Junttila et al. (2021) has demonstrated the feasibility of using optical and thermal data from MODIS 1 km product combined with eddy covariance measurement for estimating GPP and ecosystem respiration in northern boreal peatlands.

National scale monitoring

A review by Bellassen et al. (2022) shows that many member states in the EU still use Tier 1 approaches to estimate emissions from drained organic soils, resulting in significant uncertainty. Additionally, 50–70% of member states with drained organic soils did not estimate all sources of emissions, including off-site emissions from dissolved organic carbon, which may lead to underestimating emissions from drained peatland by up to 20%. A country-specific measurement-based emission factor (Tier 2 approach) would be required to resolve the issue and set policy targets.

As an example, in Finland, approximately 55% of peatlands have been drained, with 93% of the drained area utilized for forestry (Turunen and Valpola 2020) and therefore vegetation based classification is widely applicable across the country. The extent and impact of forest drainage on a site are primarily determined through the examination of tree growth and the succession of understorey plant communities. While the tree cover consists of native tree species, commonly still of the original pre drainage tree individuals, the classification based on understorey vegetation comprises three classes: (1) recently drained areas still dominated by original mire plant communities (ojikko in Finnish), (2) older drained areas where $<75\%$ of the understorey mire vegetation cover has been replaced by typical boreal forest moss and shrub species (transformed peatlands, muuttuma in Finnish), and (3) drained forest peatlands where over 75% of the original mire plant communities have been replaced by forest understorey vegetation (heathy peatlands, turvekangas in Finnish; Päivänen and Hånell 2012). Data from national forest inventories also contributed to the development of a new dynamic method (Tier 3 method) for estimating the soil CO_2 balance (the difference between carbon added to the soil via litter input and CO_2 lost through soil organic matter decomposition) in drained peatland forests, considering vegetation and climate factors (Alm et al. 2022). This method employs empirical regression models and time series data of tree basal area, air temperature, and drained peatland forest site type for the national GHG inventory. It addresses the lack of direct nationwide data on water table depth, which would be the primary factor influencing decomposition in drained peatlands (e.g., Evans et al. 2021). The impact of water table depth on decomposition is incorporated through the effect of tree basal area, which serves as a proxy for the rate of evapotranspiration that controls water table depth. Tree basal area also predicts litter input from vegetation. Moreover, the new dynamic method accounts for changes in harvesting rates and the influence of climate warming.

Resampling and analysis of previously surveyed sites provide an accurate assessment of peatland condition. In Denmark, approximately 10,000 agricultural peat sites were sampled in 2009/2010 to strengthen the national inventory of peatlands. In 2020/2021, 1000 sites were revisited to establish the changes in SOC content and peat thickness. Figure 16

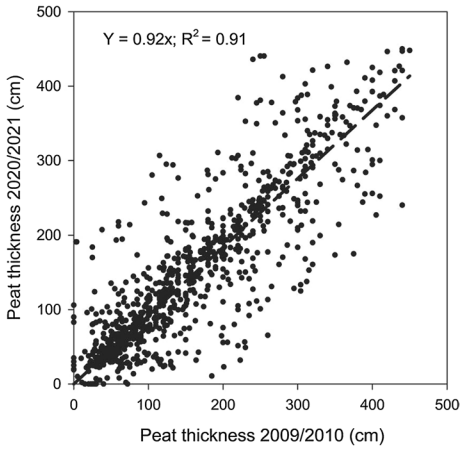

Fig. 16 Peat thickness measured in 2020–2021 as a function of peat thickness measured in 2009–2010 for 922 sampling sites located in agricultural peatland areas. Sites displaying a peat thickness smaller than 450 cm were selected from the initial 1000 points, and extreme outliers (Δ thickness > 200 cm) were removed

illustrates the variation in peat thickness over the 10-year period. This preliminary result confirms a continuing subsidence of Danish peatlands. Furthermore, since most of the investigated soils had been cultivated and drained for more than 50 years before the original sampling, the observed subsidence represents continued subsidence in heavily degraded peatlands rather than the initial subsidence associated with draining pristine wetlands (Wösten et al. 1997). This information could form the basis of estimating carbon emissions from peat degradation, and provide insights into the hydrological functioning of peatlands, which may affect water quality and quantity.

Global scale monitoring

There is limited reporting to the UN Climate Convention Framework on Climate Change (UNFCCC) of the emissions associated with peatland drainage and degradation, especially from the non-Annex I countries. To support country reporting and to build a global knowledge product, the Food and Agriculture Organization of the United Nations (FAO) since 2013 has published a FAOSTAT database on the GHG emissions associated with the drainage of organic soils due to agricultural activities (FAO 2020; FAO 2023; Conchedda and Tubiello 2020).

Estimates are currently available for the period 1990–2020 for all countries and territories. The dataset includes activity data (i.e. hectares of organic soils drained for agriculture); and GHG emissions (in kilotonnes of N_2O and CO_2) by cropland and grassland organic soils separately. The estimates are computed spatially, using the Tier 1 methods of the IPCC Guidelines for National GHG Inventories (IPCC 2014) and using the map of histosols distribution. The time series relies on annual land cover maps from the European Space Agency Climate Change initiative [ESA CCI land cover, currently under the European Copernicus program (2019)].

Results validated against available national data reported to the UNFCCC showing a good correspondence (Conchedda and Tubiello 2020) in particular for Indonesia. The dataset thus can serve as a reference for countries where analytical and statistical capacities on drainage of peatland and associated emissions are still under development.

FAOSTAT information is a key contributor to the relevant indicator in the UN Statistical Division (UNSD)/UNFCCC global set of climate change statistics and indicators. It has also been recognised as a valuable source of information in the sixth IPCC assessment report and the most recent Global Carbon Budget (Friedlingstein et al. 2022).

FAOSTAT estimates of the emissions from drained organic soils largely depend on the global map of histosols. Recent advancements in the mapping of national and global peatlands as those described in the previous sections are expected to provide an additional source of information for future updates.

FAOSTAT also provides information on peat fires at country, regional, and global levels for the period 2001–2021, using geospatial analysis using MODIS data on fires and annual land cover information. However, these estimates of emissions have a high level of uncertainty (IPCC 2014) due to their reliance on coarse-scale remotely sensed data of burning biomass in areas where organic soils are indicated on the map. The presence of fires is not always a reliable indicator that the underlying peat layer is burning, and remote sensing has limited capacity to detect the smoldering fires that are typical of peatlands. It is primarily a tool to identify potential national hotspots rather than to evaluate national GHG inventory data.

Table 2 A summary of monitoring approaches based on proxy at various spatial scales for assessing peatland conditions and functions like greenhouse gas (GHG) emissions, carbon (C) stock and others

Scale of measurement	Indicators/measurements	Peatland conditions and functions
Plot	Degree of humification, dry bulk density	GHG emissions, nutrient and dissolved organic carbon fluxes, peat degradation and restoration progress
	Stoichiometric ratio	Nutrient cycling and export, peat degradation and restoration progress
Field to landscape	Proximal sensing: e.g. gamma radiometrics, electromagnetic induction	Peat thickness for C stock and management, peat moisture content, water table height, hotspots for GHG emissions
	Remote sensing: UAV-based sensing	Land cover change, erosion and drainage structures, vegetation mapping for peatland management
Regional to National	Active Remote sensing: InSAR, Lidar	Subsidence rate, Water table, peat moisture, landslides for hydrological functions and restoration potential
	Optical images combined with modelling	GHG emissions
	Repeated field sampling	C and nutrient stock and GHG emissions
Global	Land use change and fire	GHG emissions (Tier 1)

Caveats and limitations

Many proxy approaches have been explored to monitor peatland conditions from its thickness to physical and chemical properties to inform peat conditions and functions (Table 2).

Restoration of peatlands mostly aims to limit fires, mitigate GHG emissions and increase carbon sequestration. Monitoring aims to understand and quantify the long-term effects of rewetting on peatland carbon fluxes and ecosystem services. While measurement of GHG fluxes using eddy covariance is essential, providing semi-continuous measurements over reasonably large land footprints (hectares), it remains expensive and technically demanding and can only be employed at a limited number of locations. Chamber measurements of GHG fluxes are labour-intensive, sample very small areas (< 1 m^2), and cannot be deployed over tall vegetation such as forests. While both approaches can be used to monitor representative sites, and thereby derive emission factors, it is not currently possible to measure GHG fluxes directly as part of every individual peat emissions mitigation or restoration project. Therefore, monitoring of peatland conditions for evaluating restoration schemes needs to consider local proxies, combined with remote sensing and/or modelling approaches. Current and future high resolution laser scanning and hyperspectral earth observation missions could serve this purpose. While strong proxies for some elements of the net ecosystem carbon budget of peatlands exist, e.g., water table depth for carbon dioxide fluxes, there is still a dearth of published studies on the success of proximal and remote sensing modelling in detecting changes in peatland conditions, such as water table depth, peat surface elevation and carbon fluxes, in particular to upscale from field and regional scale pilots to national and global estimates, and to allow countries to move from IPCC Tier 1 default emission factors to higher-tier approaches based on robust, empirically based and practical methods. In addition, there is still a challenge in developing such approaches for monitoring peatlands for nutrient cycling water retention, and biodiversity protection beyond the level of broad ecosystem type classification.

While strong proxies for determining GHG budgets across the spectrum of degradation in peatlands are nearing operational level as tools for e.g., national inventories, consistent broad-scale monitoring of natural and rewetted peatlands to evaluate their ecosystem functioning is still lacking. In part due to the relatively recent onset of widespread restoration programmes, and in part due to funding constraints on individual projects which tend to support short-term restoration work but not long-term outcome monitoring. Post-rewetting dynamics of carbon cycling in peatlands are still poorly monitored and limited to short-term studies of less than 3 years in most cases (Tiemeyer et al. 2020; Evans et al. 2021). As a result, predictions of the GHG benefits are often reliant on

comparison of different sites (i.e. space-for-time substitution) rather than direct monitoring over restoration transitions, which may involve transient periods of either higher emission (e.g. of methane or nitrous oxide following re-wetting of agricultural land), or periods of elevated CO_2 uptake as degraded ecosystems rebuild their above and below-ground carbon stocks. In some rewetted peatlands, particularly those where water level fluctuations are large in range or include periodic inundations, methane fluxes have been noted to be significantly larger than a mean water table depth proxy would suggest (e.g., Tiemeyer et al 2020). Published studies (e.g. Couwenberg et al. 2011; Tiemeyer et al. 2020; Evans et al. 2021) indicate that methane emissions can vary widely between sites with similarly high water tables, implying that additional factors such as nutrient status and vegetation type have an additional influence on emissions. In some cases, elevated emissions following rewetting can continue for a decade, in line with a shift in the recovering vegetation community (e.g., Antonijević et al. 2023), while in others the recovery of the ecosystem is more rapid and the overall GHG outcomes are more favourable. Thus, while national level mapping and monitoring instruments for the major components of the ecosystem carbon balance such as carbon dioxide, methane and potentially nitrous oxide are probably not too far away from being successfully applicable, site-level monitoring and verification may still require consideration of additional drivers.

For local peatland conditions, monitoring of peat soil characteristics like the degree of humification or elemental ratios is essential, and the collection of robust baseline data should be mandatory before rewetting of peatlands, in particular if downstream systems are vulnerable to higher nutrient input but also to assess the nutrient mobilization in rewetted peat soils (Zak et al. 2018). As mentioned above, high mobilisation of nutrients but also other substances like DOC and POC as potential harmful substances for adjacent aquatic ecosystems depend strongly on the degree of peat decomposition (Sect. "Monitoring at profile scale: peat soil indicators"). However, as for GHG fluxes, the range of concentrations of dissolved substances like phosphate may vary by one to two orders of magnitude in rewetted peat soils due to varying importance of biogeochemical processes, e.g., decomposition of organic matter, redox processes, nutrient uptake by plants and microorganisms, or formation of minerals (Walton et al. 2020). Eventually, the risk of high export of polluting substances to downstream systems depends on hydrological conditions, specifically on water pathways and fluxes which are, however, difficult to assess and thus often unknown or highly uncertain (Petersen et al. 2020). The knowledge of soil characteristics and hydrology is important both for modelling nutrient and carbon cycling in wetlands and, eventually, for prioritising, planning and successfully implementing wetland restoration measures and designing their sustainable management (Zak and McInnes 2022). However, the large heterogeneity of soil properties in space and time (Negassa et al. 2022), the complex hydrology (Wang et al. 2021) and knowledge gaps regarding microbial dynamics and functioning as drivers of carbon and nutrient cycling (Weil et al. 2020) still cause large uncertainties in the assessment and prediction of their ecosystem functioning (Jurasinski et al. 2020).

Monitoring after rewetting of peatlands is also essential in order to verify restoration outcomes, and in case of side effects like elevated methane emissions or nutrient swapping to develop an adaptive management as requested by the IUCN standard for labeling the restoration action as nature-based solution (IUCN 2020). These requirements are particularly important in the case of projects funded via 'payment for ecosystem service' schemes, for example those that generate carbon credits, to ensure that these credits are verifiable. These requirements are being increasingly written into high-quality schemes such as the UK Peatland Code and Germans Moor Futures schemes. This should ensure best practice restoration methods are developed and implemented to maximise the benefits of peatland rewetting and restoration, ensuring that peatland management contributes to the zero emission future in the spirit of the UNFCCC and the Paris Agreement. As Günther et al. (2020) conclude, methane's "radiative forcing does not undermine the mitigation potential of peatland rewetting" and advancing with the rewetting of all drained peatlands as fast as possible would be the most efficient course of action.

The existing research evidence on the resilience of rewetted peatlands, when compared to their baseline degraded or near-natural state, remains relatively limited. Studies mainly focus on observations during extreme events rather than comprehensive modelling studies under future projected climates. Some studies,

such as Beyer et al. (2021), have demonstrated positive outcomes in terms of resilience to drought and carbon functioning. However, it is essential to approach these findings with caution, as highlighted by Loisel and Gallego-Sala (2022). They caution that while rewetting can lead to improvements in carbon functioning, hydrological functioning, and biodiversity may not be fully restored even after a decade, as observed in studies like Kreyling et al. (2021). This incomplete restoration could potentially result in weakened resilience to climate change impacts when compared to natural peatland states. The resilience of rewetted peatlands to climate change could be tested in the likely more extreme wildfires expected to occur. It is possible that residual peat thickness (e.g. Moore et al. 2021), water levels (e.g. Shepherd et al. 2023) and whether or not the mechanical feedbacks (e.g. 'bog breathing') on surface moisture content have been functionally restored (e.g. Andersen et al. 2021) will determine the degree to which rewetted peatlands are resilient to future wildfire events.

Conclusions

Peatland ecosystems have gained global policy interest due to their immense carbon stores, GHG emissions when degraded, their unique biodiversity and the role in regulating water, but their extent and status remain uncertain in many parts of the world. Based on our review we can conclude the following:

- Carbon fluxes from degraded and drained peatlands account for significant emissions, but national and global estimates of GHG emissions from peatlands are reliant on limited data. Accurate mapping and inventories of peatlands are necessary to locate degradation hotspots and enable prioritization of restoration and resultant emissions reductions and avoidance. Approaches based on robust proxies are now being assessed at various fields to regional scales, with promising results.
- Improved mapping at a finer scale, using remote sensing, will enhance our understanding of different peatland conditions, and thus guide management practices to reduce GHG emissions and promote sustainable land use and development. Repeated mapping can track changes in land use and carbon stocks over time, to ensure that policies and practices are effective in reducing and avoiding emissions from land use, land-use change and land degradation, thus enabling climate targets to be achieved.
- Peatlands are biodiversity hotspots, providing habitats for numerous plant and animal species that are unique to these ecosystems. The diverse characteristics of peatlands around the world provide an additional contribution through their valuable ecosystem diversity. By understanding the rate of conversion and degradation of peatlands, conservation efforts can be focused on protecting, restoring and sustainably managing these critical ecosystems.
- Having a consistent definition and approach to mapping peatlands might avoid today's discrepancies in peatland area coverage. Currently, different regions use various definitions which lead to inconsistencies. However, a single, globally applicable approach to peatland diversity and their use may not be possible, but future efforts can focus on mapping carbon stock with at least regionally harmonized approaches. This would enable alignment and comparability across countries and regions which is important for capturing peatlands' significant contribution to many multilateral environmental agreements, global and regional goals and targets.
- More comprehensive monitoring before and after peatland rewetting is needed, spanning larger spatial and temporal scales. This would ensure that appropriate decisions are made about restoration or adaptive management to avoid negative consequences, ensure that carbon and other ecosystem benefits are verifiable, and thus optimise benefits to human society.
- Simple peat characteristics such as degree of humification, dry bulk density or stoichiometry can be used as a proxy to estimate the carbon and nutrient fluxes in different degraded peatlands. However, due to the high complexity and temporal changes of biogeochemical and hydrological processes and driving factors both under aerobic and anaerobic soil conditions, the measurement of single parameters like the dry bulk density or stoichiometric ratios will be not sufficient to make a reasonable estimate of carbon and nutri-

ent sink function of rewetted peatlands neither in short-term nor in the long-term perspective.
- Remote and proximal sensors have the potential to monitor peatland conditions and functions. However, it is important to acknowledge that sensors have their own capabilities and limitations and often even more field measurements are still required to calibrate the measurements and assure high quality results.
- Most studies on peatland restoration focus on GHG emissions. Future work of monitoring needs to consider also various peatland ecosystem services, such as biodiversity and pollution control, in addition to climate change mitigation.
- By increasing research collaboration across disciplines, countries and regions we can advance peatlands monitoring and mapping to make decisions that will help combat nature, climate and pollution crises.

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Declarations

Conflict of interest The authors declare no competing interest.

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