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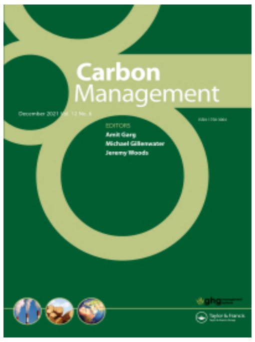

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The three-peat challenge: business as usual, responsible agriculture, and conservation and restoration as management trajectories in global peatlands

Nicholas T. Girkin[a,b], Paul J. Burgess[a], Lydia Cole[c], Hannah V. Cooper[b,d], Euridice Honorio Coronado[c], Scott J. Davidson[e], Jacqueline Hannam[a], Jim Harris[a], Ian Holman[a], Christopher S. McCloskey[a], Michelle M. McKeown[f], Alice M. Milner[g], Susan Page[h], Jo Smith[i] and Dylan Young[j]

[a]School of Water, Energy and Environment, Cranfield University, Cranfield, UK; [b]School of Biosciences, University of Nottingham, Nottingham, UK; [c]School of Geography and Sustainable Development, University of St Andrews, St Andrews, UK; [d]Sustainable Soils and Crops, Rothamsted Research, Harpenden, UK; [e]School of Geography, Earth and Environmental Sciences, University of Plymouth, Plymouth, UK; [f]School of Biological, Earth and Environmental Sciences, University College Cork, Cork, Ireland; [g]Department of Geography, Royal Holloway University of London, Egha, UK; [h]School of Geography, Geology and the Environment, University of Leicester, Leicester, UK; [i]School of Biological Sciences, University of Aberdeen, Aberdeen, UK; [j]School of Geography, University of Leeds, Leeds, UK

ABSTRACT

Peatlands are a globally important carbon store, but peatland ecosystems from high latitudes to the tropics are highly degraded due to increasingly intensive anthropogenic activity, making them significant greenhouse gas (GHG) sources. Peatland restoration and conservation have been proposed as a nature-based solution to climate change, by restoring the function of peatlands as a net carbon sink, but this may have implications for many local communities who rely on income from activities associated with transformed peatlands, particularly those drained for agriculture. However, without changing the way that humans interact with and exploit peatlands in most regions, peatlands will continue to degrade and be lost. We propose that there are ultimately three potential trajectories for peatland management: business as usual, whereby peatland carbon sink capacity continues to be eroded, responsible agricultural management (with the potential to mitigate emissions, but unlikely to restore peatlands as a net carbon sink), and restoration and conservation. We term this the *three-peat challenge*, and propose it as a means to view the benefits of restoring peatlands for the environment, as well as the implications of such transitions for communities who rely on ecosystem services (particularly provisioning) from degraded peatlands, and the consequences arising from a lack of action. Ultimately, decisions regarding which trajectories peatlands in given localities will follow torequire principles of equitable decision-making, and support to ensure just transitions, particularly for communities who rely on peatland ecosystems to support their livelihoods.

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Introduction

Peatlands are a globally important carbon store, covering only 3% of the Earth's terrestrial surface, but accounting for 25% of global soil C, equivalent to over 600 GtC (Yu et al. 2010). Anthropogenic change is adversely affecting peatlands across the globe, including boreal, temperate, and tropical peatlands [1,2]. More than 50% of the global wetland area, which includes peatlands, has been lost since 1700 CE, driven by land use change [3]. At present, human activity, including drainage, afforestation or mining, has affected between 10% and 15% of global peatlands [4,5], equivalent to 505,680 km^2, with approximately 5000 km^2 being drained per year between 1990 and 2017 [6]. These ecologically and hydrologically degraded ecosystems are becoming increasingly vulnerable to further environmental change, particularly climate change impacts [7].

In Europe, significant drainage and mining of lowland peatlands began in the Netherlands during the mediaeval period, with peat used as a fuel for the production of tiles, glass, ceramics and for the baking and brewing industries. During the same period, but on a smaller scale, peatlands in the UK were also cut to provide fuel for heating,

CONTACT Nicholas T. Girkin n.t.girkin@cranfield.ac.uk, Nicholas.girkin@gmail.com School of Water, Energy and Environment, Cranfield University,Cranfield, UK; School of Biosciences, University of Nottingham, Nottingham, UK

for example, resulting in the creation of the shallow Broadland lakes in eastern England [8,9]. In subsequent centuries, peatlands in northern Europe were drained to increase available agricultural land, both for livestock raising and crop production, and also for forestry, particularly in Russia, Finland and Sweden. Peat extraction for electricity production and heating continues in a small number of northern European countries, as well as in the tropics in Rwanda, while mining of peat to provide growing media (for example for potting composts sold globally) is focused in Canada, Ireland and some Baltic states. Until relatively recently, anthropogenic impacts on tropical peatlands have been limited, with most changes only occurring since the late twentieth century [2]. In Southeast Asia, approximately 50% of the peatland area is now under either large-scale plantations of oil palm or pulpwood, or smaller-scale agriculture, with most of this conversion occurring since 1990. One of the largest conversion schemes was Indonesia's Mega Rice Project which occurred between 1995 and 1999 and aimed to convert 1 Mha of peatlands on the island of Borneo to rice production. Although this project was never fully realized, the resulting deforestation and drainage led to the loss of forest biodiversity and increased fire vulnerability. During the 1997 El Niño driven drought, fires on drained Indonesian peatlands, including in the Mega Rice project area, ultimately resulted in the loss of up to 2.57 GtC [10]. Tropical peatlands in Central Africa and South America have been subject to lower levels of human impact, but there are concerns about their increasing exposure to resource exploitation, including oil and gas exploration and production [11], and timber extraction and plantation or agricultural development [12,13]. Peatlands across the small island nations of Oceania are also threatened by drainage, area loss, fire, cultivation, and grazing by pigs, cattle, and goats [14]. There is evidence that taro (*Colocasia esculenta)* cultivation on some peatlands in Papua New Guinea has occurred for at least the past 10,000 years [15,16]. At a smaller scale, wetland taro is still an important commercial crop in Fiji, Vanuatu, New Caledonia, Kiribati, Cook Islands, Wallis and Futuna, among others.

While some of the most extensive fires on peatlands in recent decades have occurred in Southeast Asia, fire is of increasing concern for peatlands in other climate zones. In the UK, upland peatlands continue to be damaged by various land uses or combinations of land uses (for example sheep grazing and management for game bird shooting) that involve burning. As a result, many areas have become drier and dominated by dwarf shrubs [17,18], making them more susceptible to fire, which could be exacerbated by climate change [19]. However, the management of these peatlands to reduce the likelihood of wildfires is contested with some studies advocating the burning of shrubs to reduce fuel load [20] and others proposing that continued restoration to rewet peatlands is needed [17]. The impact of managed burning (whether for wildfire mitigation or to improve upland peatland habitat for bird breeding and shooting) on peatland C stocks is also contested. Past C accumulation rates cannot be determined directly from peat core records and compared through time because peat is not inert and can therefore be affected by climate or land-use change centuries after it became part of the peatland [21]. However, a recent review of the scientific evidence [22] concluded that there is increasing consensus that burning damages blanket peatlands, and the authors identify stopping burning as an important aspect of peatland protection and restoration. Legislation in the UK now restricts the burning on peat deeper than 40 cm in protected blanket bogs (The Heather and Grassland etc. Burning (England) Regulations 2021). Boreal peatlands represent a large wildfire fuel source, and although they typically experience low-severity fires, increasing wildfire frequency and severity under a changing climate is threatening vast areas of boreal peatlands globally [23]. Wildfires can have a significant impact on the magnitude of C fluxes from boreal peatlands, releasing up to 85 kg C m^{-2} through combustion and smoldering [24]. Furthermore, enhanced use of boreal peatlands for forestry and oil and gas industries increases rates of drainage, in turn increasing the risk of fire. In a recent study, Wilkinson et al. (2023) estimated that wildfire processes across boreal and temperate peatlands in northern regions can reduce C uptake in pristine peatlands by 35%, and further enhance C emissions from degraded and drained peatlands by 10%. Peatland fires are not only a source of GHG emissions to the atmosphere, but also of fine particulates, other gases and aerosols which reduce air quality and are damaging to human health [25]. All such anthropogenically driven changes stand in contrast to historic low-impact human activity in peatlands, for example by communities in the tropics, which did not result in large-scale landscape transformations [1,2].

Under the Paris Agreement, the world is committed to achieving increasingly ambitious GHG emissions reductions to limit global warming. This requires rapid transitions away from fossil fuel use and better management of land resources to reduce emissions and/or drawdown atmospheric GHGs [26]. Disturbed peatlands, particularly those drained for agriculture, are a major source of CO_2 emissions from rapid and continuous aerobic decomposition, whereas the restoration and conservation of peatlands have substantial climate change mitigation potential [1,27] and can also reduce the incidence and severity of peatland fires [1,19].

In the context of global peatlands, we highlight three potential trajectories that peatlands may follow in the coming decades, with significant implications for the global C cycle; conservation and restoration, responsible agricultural management, and "business as usual" **(**Figure 1). The conservation and restoration, and responsible agricultural pathways for enhancing the role of peatlands as a nature-based solution (solutions to societal challenges that involve working with nature [28], have distinct advantages and limitations. We propose that ultimately the majority of global peatlands will need to follow the first two trajectories, with essential financial support for farmers and farming communities working within peatlands and relying on provisioning ecosystem services, and continued support for income activities that do not involve large-scale modification of the landscape (for example traditional management of tropical wetland environments) [29]. The third trajectory should be restricted to highly degraded ecosystems where restoration is unlikely (for example due to prohibitively high costs, technical feasibility, or substantial negative impacts for local communities), or where there is an interim need to balance climate and food/livelihood security as a transition to full ecosystem restoration in some localities. We describe these three trajectories as the "three-peat challenge" with each pathway affecting the three dominant peatland regions; boreal, temperate, and tropical. Different trajectories are ultimately likely to be suitable for different regions and localities, reflecting local idiosyncrasies, but ultimately peatland management must be used to move these ecosystems away from the business-as-usual trajectory. To underpin this transition to more environmentally responsible trajectories, we also highlight the opportunity and need for sharing knowledge

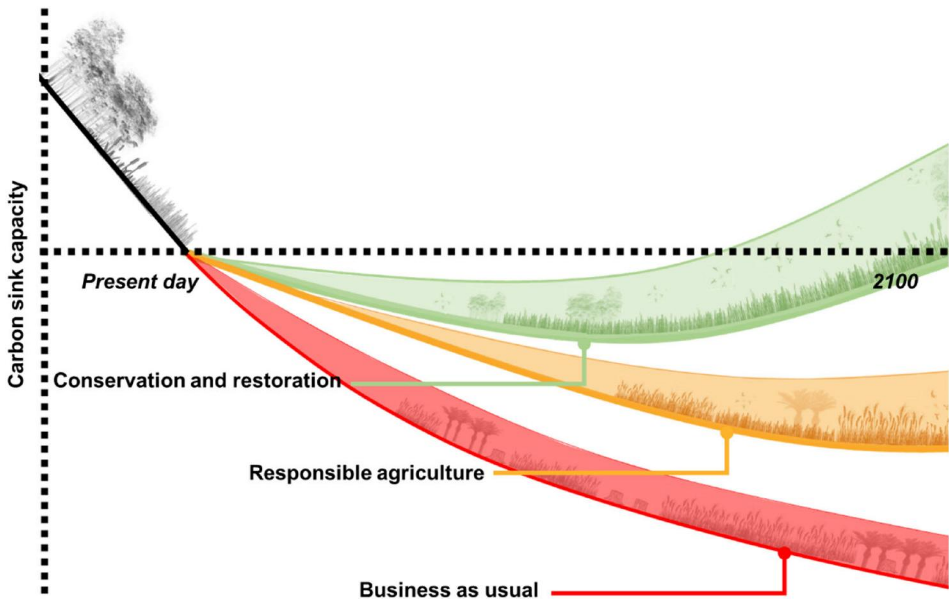

Figure 1. The three-peat challenge describes three contrasting trajectories for peatland management: business-as-usual, responsible agriculture, and conservation and restoration, as a way to understand the potential impacts of these types of management practice or intervention on peatland C dynamics. The dotted line on the X-axis represents time, while band thickness is an approach for visualizing potential global peatland C sink capacity (above and bel. Under business-as-usual (thin red band), peat degradation will continue or intensify, with increased exploitation for agriculture and other land uses and management practices (for example Sub-surface exploration for petroleum resources), with minimal carbon sink potential and high GHG emissions. Responsible agriculture (medium thickness yellow band) may offer benefits (for example reduced GHG emissions and increased biodiversity) over business-as-usual, whereas conservation and restoration (green band, maximum thickness) can result in restoring the role of peatlands globally as a net carbon sink. This approach is illustrative, as different solutions will need to be implemented based on local requirements (dictated by, for example, geography, natural resource availability, and livelihood practices), and there is likely to be a need for the implementation of both responsible agriculture and conservation and restoration approaches together.

between such regions, whilst acknowledging differences in local to regional characteristics, to address this challenge. The aim of this paper is therefore twofold: 1. to develop the concept of the three-peat challenge as an emerging approach for characterizing the potential management trajectories of peatlands, and through which to understand the consequences of contrasting types of management interventions; and 2. review the potential impacts of management interventions within each trajectory on potential C gains and losses.

Business as usual

Under a business-as-usual trajectory, global peatlands will continue to be exploited for agriculture and other land uses, resulting in substantial degradation and loss of ecosystem function, particularly carbon sequestration. Across the globe, degraded peatlands may account for up to–2 - 5% of current anthropogenic GHG emissions [5,30,31], and up to 10% of global CO_2 emissions [32]. Drained, lowland agricultural peatlands account for 32% of global cropland emissions, but only contribute approximately 1% of crop calories [33]. In the UK, it has been estimated that peatlands emit about 23 Mt CO_2e yr^{-1} [34], equivalent to 5% of the UK territorial GHG emissions of 458 Mt CO_2e yr^{-1} in 2019. Between 1990 and 2010, the expansion of oil palm plantations in Indonesia and Malaysia accounted for over 10% of peatland deforestation, with 2.3 Mha of peat swamp forest clear-felled [35]. Coupled with drainage, this has resulted in substantial oxidative peat loss and GHG emissions. Cooper et al. (2020) estimate that the conversion of Southeast Asian peat swamp forest contributes between ≈–7–28% of combined total national GHG emissions from Malaysia and Indonesia, equivalent to ≈–4 – 0.7% annual global emissions [36]. Remaining stored C is also highly vulnerable to release following further disturbance [37] or changes in temperature [38]. Globally, typical ongoing rates of peat loss drained for agricultural use are approximately 2 cm yr^{-1} which can have adverse effects on agricultural productivity [33,39]. Oil spills and the development of new infrastructure are also contributing significantly to the degradation and loss of peatlands, and ecosystem service provision [11,12,40]. In addition to this, peatland ecosystems where direct anthropogenic activities are limited or are of low impact will also be indirectly affected by the impacts associated with the Anthropocene, including climate change, which will alter hydrological regimes and increase fire risk, and ultimately reduce the resilience of peat-forming ecosystems [1,2].

The scale of such peatland losses and associated emissions from degraded global peatlands, alongside declines in peatland resilience due to the indirect impacts associated with the Anthropocene, is likely to increase without changes in management. In the context of the need to increase food production by 60% by 2050 to feed a growing global population [41], peatlands may come under increasing pressure through the maintenance or expansion of existing areas of agricultural production.

Responsible management of peatlands for farming and other uses

Responsible management of peatlands for farming represents an alternative, possibly intermediate trajectory for peatland management, although it should not be viewed as an alternative to the conservation and restoration pathway. Extensive areas of peatland globally have been converted for agriculture, with higher-profile examples including the East Anglian Fenland farming landscapes in the UK, producing 7% of England's agricultural production [42], and the expansion of oil palm agriculture in Southeast Asia [36]. Greenhouse gas emissions from peat soils under agricultural management vary with land cover, temperature and drainage status. For example, in the UK, the level of combined CO_2, CH_4 and N_2O emissions from drained lowland peat soils (i.e. excluding nitrous oxide emissions) have been reported up to 38.98 t CO_2e $ha^{-1} yr^{-1}$ for drained cropland, 19 t CO_2e $ha^{-1} yr^{-1}$ for extensive grassland, 29.89 t CO_2e $ha^{-1} yr^{-1}$ for intensive grassland, compared to 9.91 t CO_2e $ha^{-1} yr^{-1}$ for woodland [34,43]. For grasslands overlying shallow peat, reducing rates of crop biomass removal may also provide some benefits if a part of this biomass is incorporated into the peat, assuming it is not decomposed [34].

Despite the extensive adverse environmental impacts of continued conventional farming on peatlands, there is a growing body of literature focused on specific farming practices that may have the potential to reduce emissions. These more responsible farming practices may bring some benefits in terms of reducing rates of peat loss while continuing to support crop production and farmer and community livelihoods. Such practices include zero-tillage, intercropping and cover cropping, and incorporating livestock, and are being increasingly applied in farming systems on mineral soils as part of a suite of regenerative farming practices, although the precise impacts for peat soils are unclear [44]. However, in general, any ongoing intensive farming practices are likely to drive ongoing and extensive degradation of remaining peat C, and loss of other ecosystem services [34].

The potential impacts of the adoption of "regenerative agricultural practices" for peatlands are uncertain, as many key pathways and processes remain poorly quantified (Figure 2). When combined with raised water tables, cover crop cultivation during uncultivated periods may reduce net GHG emissions and nitrogen leaching [45]. Wind erosion is a particular risk facing bare organic soils [46] which might be mitigated by cover cropping during otherwise fallow periods. There are however significant uncertainties regarding the long-term impacts of supposedly sustainable agricultural practices such as cover cropping. These may include additional C mineralization due to potential positive C priming effects from labile C inputs through rhizodeposition (i.e. increased decomposition of more recalcitrant organic matter through exudates from plant roots) and addition of C in root biomass; evidence for this occurring in peatland soils is currently inconclusive [47,48]. Similarly, intercropping may provide similar benefits, as well as a potential route for income diversification for smallholder farmers in the tropics [49], but may have additional tradeoffs through increased production of GHGs [50], particularly of N_2O [51].

Despite benefits from zero-tillage being demonstrated on mineral soils, evidence suggests that the practice offers only minimal benefits for agricultural peats. Zero-tillage combined with seasonal water table manipulation requires no change in land use but offers only modest emissions savings [41]. Similarly, Taft et al. (2018) found that the introduction of zero- or minimum-till practices may not reduce GHG emissions across peatlands in East Anglia in the UK and that maintaining a high-water table was the only option that reliably reduced GHG emissions [52]. Similarly, despite these potential benefits from a shift to regenerative farming practices compared to "business as usual" scenarios, Evans et al. (2017) suggest that modifications in tillage and agricultural cropping practices are likely to overall have a minimal effect on GHG emissions [34]. Instead, the main method to reduce GHG emissions from drained peatland is to rewet the soil, as rewetted bogs or fenlands can result in close to zero CO_2 emissions. A typical rule of thumb is that every 10 cm increase in the water table can reduce emissions by about 3 t CO_{2e} $ha^{-1}\,yr^{-1}$ [53]. However the increased loss of CH_4 from re-wetting can still result in net losses (excluding N_2O) of–1 – 6 t CO_{2e} $ha^{-1}\,yr^{-1}$, compared to minimal net emissions of natural bog or fenland [34]. Dawson and Smith (2007) reported that shallower water tables on peat soils can reduce the rate of GHG emissions by–5 – 15 t CO_{2e} $ha^{-1}\,yr^{-1}$ [46]. Evidence suggests that farming can continue under conditions of higher water table depth, albeit with potential tradeoffs in terms of agricultural production [54]. A significant additional benefit of elevated water tables includes reduced fire risks, both in tropical and high-latitude peatlands [19].

Paludiculture has been described as "farming and agroforestry systems designed to generate a

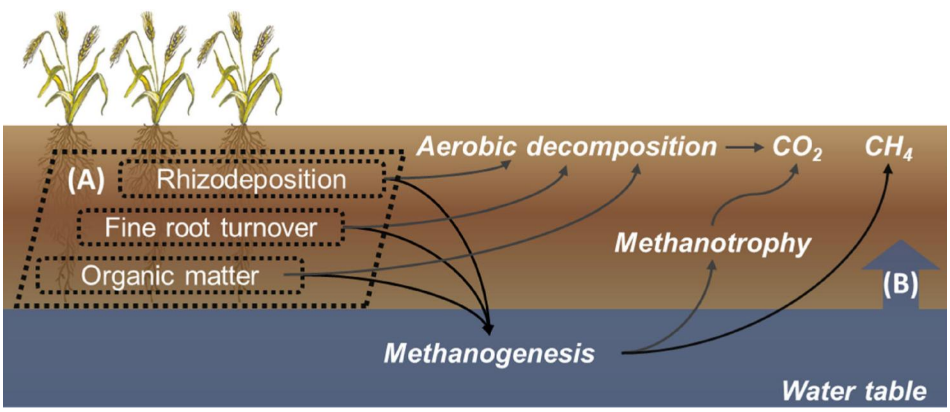

Figure 2. Belowground C dynamics in agricultural peatlands and key processes likely to be affected by changes in management including (A) potential C priming processes from changes in dominant vegetation and management (for example cover cropping), and (B) changes in water table affecting rates of oxidative peat loss versus methanogenesis, as part of a higher water table or paludiculture farming system. Elevated water tables have the greatest potential for emissions mitigation and may still support crop production.

commercial crop from wetland conditions using species that are typical of (or tolerant of) wetland habitats" [53]. Such practices are increasingly being explored globally, in both tropical and temperate environments, as a potential means to continue to support farmer livelihoods in peatland landscapes, with an emphasis on the use of local species that have financial viability and potential ecological benefits [55,56]. For example, Mulholland et al. (2020) reported that paludiculture could result in a reduction in emissions of–4 – 13 t CO_2e ha^{-1} yr^{-1} for UK temperate peatlands [53].

In contrast to higher latitude peatlands, recent social science research has provided insights into the traditional uses of tropical peatlands, revealing that farming has not been a common practice. Instead, activities including hunting, gathering, fishing and, to a lesser extent, timber extraction have been prevalent [29]. Recognizing the importance of peatlands, the Peruvian regulatory framework now includes norms and instruments for the conservation and sustainable management of wetlands and peatlands [57]. Recent advancements have been made in the form of new peatland-specific mitigation actions to be included in nationally determined contributions (NDCs). For example, to reduce emissions from peatlands, Peru will give priority to the establishment of new conservation areas on peatlands, promoting sustainable management of non-timber forest products, implementing fishery management programs and recognizing the peatland knowledge, practices and values of indigenous communities related to peatlands [58].

Other land uses on peats include for energy generation, for example by onshore wind, hydroelectric, solar and geothermal schemes. Onshore wind, in particular, is often sited on exposed upland sites, which in the UK, Ireland and Spain, tend to be peatlands. For example in Scotland in 2014, 62% of wind farms were located on peat soils [59]. Drainage of peatlands around infrastructure (for example turbine bases, roads and cable channels) can result in increased emissions of C that exceed the fossil-fuel C savings provided by the wind farm [60]. Therefore, infrastructure should be located and designed to reduce the peat volume drained [61]. With decarbonization of the energy grid, siting wind farms on peatlands is becoming increasingly less beneficial to the climate, so future policy should avoid constructing wind farms on peatlands unless technologies (such as piling) can be developed to minimize drainage and volume of peat excavated for the turbine foundations [62].

Peatland conservation and restoration

A conservation and restoration trajectory has the greatest potential to restore the function of peatlands as a net carbon sink. Approximately 75% of peatlands are estimated as being in a relatively undisturbed state [63]. Of degraded peatlands, 47% are found in the tropics, while 32% are boreal, and 21% are temperate [64]. Extensive literature has previously highlighted the critical contribution of undisturbed peatlands as a nature-based solution for climate change mitigation, due to their globally important function as the largest terrestrial C sink [65–68]. Approximately 550 Gt C is stored within high latitude peatlands [69], with an additional, but less well constrained, 105 – 215 Gt C in tropical peatlands [70–72]. There have been extensive recent efforts to improve models of distribution of peat-forming ecosystems and peat C stocks, particularly within tropical latitudes (for example the Peruvian Amazon by Hastie et al. 2022 [73]; central Congo Basin by Crezee et al. 2022 [72]). Whilst a great extent of the peat-forming ecosystems in Peru and the two main peat-rich countries in central Africa (Democratic Republic of Congo and Republic of Congo) remain hydrologically intact, they experience limited national protection, making them vulnerable to anthropogenic land use change. Publishing more accurate models of peatland distribution is a necessary first step to understanding the distribution and size of these C-rich environments. This information is critical for the development of national policies that acknowledge and protect them (including for inclusion in NDCs), and in developing local conservation and restoration initiatives to preserve ecosystems or undertake management to improve peatland condition and increase their resilience to climate change impacts.

Peatland restoration through rewetting will likely offer substantial emission reductions, but at the expense of agricultural production and with likely adverse implications for farmer livelihoods [74]. Annual GHG mitigation potential for the restoration of all cropped organic soils has previously been estimated between 0.08 – 0.92 Gt CO_2e [30,75,76], primarily from avoided CO_2 emissions. While rewetting of peatlands reduces CO_2 emissions, it does result in an emergent source of CH_4, with some indications of elevated CH_4 emissions from restored peatland sites compared to minimally disturbed peatlands [77]. However, the short term impact of elevated CH_4 compared to reduced emissions of long-term climate forcers (CO_2 and N_2O) means that rewetting provides substantial and immediate benefits [31].

To date, most peatland restoration efforts have focused on the recovery of degraded peat habitats, ideally to their pre-disturbance states. However, ongoing habitat deterioration and climate change impacts are occurring more quickly than the ability of species to adapt, resulting in low levels of resilience [78–80]. Recovery of biodiversity and hydrological function are often minimal even following a decade of restoration [81], although the ability of peatlands to reestablish sequester C can occur relatively quickly [74]. Evidence from tropical peatlands suggests that several centuries will be required for complete recovery [1,2]. In addition, there has, to date, been no restoration of tropical peatlands at scale, so the recovery rate and effectiveness of restoration remain unknown. This does not mean that such sites should not be restored but that time, long-term monitoring and funding models are required to achieve this. The recent update of the IUCN Peatland Code [82] to include agriculturally drained UK fen peats provides an example of such a funding model, in which the purchase of C credits provides the long-term funding to support restoration and associated monitoring.

In certain situations, degraded peatlands may "self-repair" vegetation and hydrological function following a tipping point, if boundary conditions including climate and pollution levels are favorable [83]. However, these instances are unlikely to be widespread where anthropogenic activities that lead to peat degradation are ongoing. An alternative to conventional restoration and self-recovery is to seek to redefine degraded peatlands to "future-proof" their fundamental ecosystem functions and build resilience, i.e. accounting for a more dynamic baseline of ecosystem characteristics. Here, the aim is to increase the diversity and complexity of ecosystems to produce functional redundancy and resultant emergent properties, for example resilience [84], encapsulated in the phrase "same play, different actors". This also allows for "restoring forwards" to secure resilience over longer timespans [85]. While such strategies are increasingly debated in the wider literature [86], the potential application of such theories (for example assisted adaptation) to peatlands has not been widely considered. Adopting such an approach could increase resilience and lead to more rapid restoration of ecosystem function. Allowing novel plant and microbial communities in "restoring forwards" interventions may also lead to tradeoffs or unintended consequences, where, for example, C sequestration is dependent on particular species which regulate peat organic chemistry and rates of decomposition [47,87], which do not return naturally. Rewetted temperate peatlands are shown to eco-hydrologically differ from pre-drained states, including in terms of biodiversity (vegetation), ecosystem functioning (hydrology), and certain land cover characteristics [88].

Vast areas of boreal peatlands have been impacted by a variety of anthropogenic disturbances, such as forestry and oil and gas exploration. The scale of such degradation has resulted in many areas being a focus for restoration activities. Restoration of these peatlands may provide an estimated potential GHG emission reduction by 2030 of 51 Tg $CO_2e\ yr^{-1}$, based on the assumption that all degraded peatlands are restored [67]. Drever et al. (2021) estimated that restoration of all degraded and disturbed peatlands across Canada (with the majority occurring in boreal regions) would result in C sequestration of 0.2 Tg of $CO_2e\ yr^{-1}$ by 2030, although this is outweighed by simply avoiding the conversion of intact peatlands in the first place, which can provide up to 10.1 Tg $CO_2e\ yr^{-1}$ in avoided emissions in 2030 after accounting for existing disturbance and conversion [89]. Nugent et al. (2018) undertook a multi-year study looking at C dynamics in a temperate peatland restored following extensive peat extraction. This s-ite was restored using the moss-layer transfer technique with their results showing that within 15 years, the restored site became a C sink (-90 ± 18 g C $m^{-2} yr^{-1}$) [90].

In localities where the hydrological functioning of peatlands is largely intact, i.e. they have not been drained, but the ecological system has been disturbed (for example by over-harvesting of peat-forming resources), restoration may involve targeted regeneration initiatives. Peat-forming palm swamps in the lowland Peruvian Amazon, dominated by the fruit-bearing palm, *Mauritia flexuosa*, can provide important ecosystem services and income for communities living in and around them [29,91]. In communities where overharvesting of the palm's fruit, locally known as *aguaje*, using destructive harvesting methods has resulted in unsustainable extraction and thus low regeneration of *M. flexuosa* [92], the use of climbing to avoid killing the palms can recover the economic potential and support continued C sequestration in these peatlands [93,94]. An understanding of the relationship each local community has with the peatlands and the resources they contain, and how this may be changing over time (for example Schulz et al. 2019 in Peru [29]; Harrison et al. 2020 in Indonesia [95], is key to co-developing appropriate restoration and/or sustainable use pathways.

Ultimately, improved peatland conservation and restoration outcomes rely on a comprehensive understanding of peatland distribution, and to a lesser extent, C storage. This can be achieved through significant effort integrating ground-based measurements with satellite data, with a particular need for improved maps of peat location [72], extent and thickness in the tropics [96]. There is also a critical need to understand potential climate change feedbacks for peatland C sink capacity [74,97,98]. Changes in temperature and precipitation may directly or indirectly (through water table change) enhance peat decomposition and increase CO_2 and CH_4 emissions [38], but conversely may alter rates of ecosystem productivity, enhancing peat C inputs [1]. Furthermore, changes in river fluctuations due to climate change have the potential to impact the biodiversity and function of peatlands due to the significant connections between flooding regime, water table depth, tree species composition and presence of peat [7]. More intensive fire events and other anthropogenic impacts are likely to adversely affect the peatland C pool and its potential as a nature based solution to climate change [99]. Finally, transitioning away from intensive anthropogenic activity must also be accompanied by extensive support for local communities who rely on peatland ecosystems for livelihoods, or the provision of specific ecosystem services [95,99].

Implementing solutions at landscape scales: different places, different trajectories

Conservation efforts in peatlands generally require a focus on the protection of peatlands as intact hydrological units. However, peatlands do not exist in isolation – they form part of a wider landscape and fall within socio-economic contexts – and therefore the implementation of practical solutions that can deliver more positive outcomes across multiple environmental, societal and economical objectives is needed. As a consequence, determining the future trajectories for peatlands falls within wider debates regarding land sparing (large, separate areas of sustainably intensified agriculture and restored nature) versus land sharing (a mosaic of lower-intensity agriculture approaches and restored ecosystems) [100,101]. Work in tropical peatlands in Southeast Asia implies that land sparing results in the lowest environmental externalities, including for GHG emissions, while also maximizing tax revenues. In contrast, a land-sharing approach results in substantial CO_2 emissions, but also creates increased employment opportunities [102]. These and other findings indicate the substantial potential tradeoffs between environment, economic and societal factors when considering the future management trajectories of peatlands. Effective peatland policy and decision-making therefore requires a concerted effort between governments, researchers, communities and other stakeholders, to reflect this complexity and maximize the co-benefits across the environment and society. Moreover, it relies on the careful synthesis of multiple strands of evidence on the benefits and tradeoffs from different interventions for C storage and sequestration (Table 1), and other co-benefits and disbenefits (for example biodiversity). In many cases (for example the impacts of specific regenerative farming practices on peat C dynamics) the evidence base for informing decision making is incomplete, or in other cases (for example, in the use of fire in peatland management), evidence has been misrepresented or misinterpreted [17,21].

Conclusions

Given the global importance of peatlands as a potential nature-based solution to climate change, the future trajectories of peatland management are of fundamental importance to local and international policymakers. Significant uncertainties remain regarding the potential response of peatlands (both degraded and those currently minimally affected by direct and indirect anthropogenic impacts) to different environmental stresses. We emphasize the need to adopt an inclusive, place-based approach in which the principles of environmental justice and equitable sharing of benefits and tradeoffs are embedded in decision-making when considering the future trajectories of peatlands. Different solutions are likely to be needed in different regions and localities, but shared knowledge and learning can increase the effectiveness

Table 1. **Summary of selected common management interventions on the terrestrial C cycle of peatland ecosystems. Statements of certainty are based on the broad levels of agreement and uncertainty across the relevant literature as assessed by the authors.**

Management trajectory/practice	Impact on the C cycle	Agreement within the literature	Selected reference(s)
Business-as-usual			
Deforestation	Deforestation decreases aboveground C storage in peatlands	Well established	[37,103]
Drainage	Drainage drives oxidative peat C losses	Well established	[4,27,37]
Compaction and subsidence	Compaction and oxidation reduces peat C stocks	Well established	[37,104,105]
Fire	Fire increases peat C losses	Well established	[10,17,19,23]
Tillage	Tillage drives peat compaction, erosion and carbon losses	Established but incomplete	[52,106]
Fertiliser application	Fertiliser provides nutrients required for decomposition, so accelerating C loss	Well established	[107]
Responsible management			
Increased water tables, but maintained below the peat surface	Higher water tables reduce oxidative C losses	Well established	[27,108]
Conservation tillage	Reduced tillage minimises soil physical disturbance, reducing C losses	Established but incomplete	[33]
Cover cropping	Cover cropping decreases C losses on mineral soils but limited impacts reported for peat soils	Not established	[45]
Paludiculture	Wetland crops reduce C losses through lower oxidative peat loss	Established but incomplete	[53,55,56]
Tree planting	Tree planting impacts depend on site specific characteristics (for example peat depth). Tree planting on deep peat drives C losses	Established but incomplete	[56,109,110]
Conservation and restoration			
Avoided peatland conversion	Maintains peatland C sink capacity	Established	[67]
Rewetting	Complete rewetting reduces oxidative C losses	Established but incomplete	[31, 88, 108]
Non-destructive resource extraction	Non-destructive extraction maintains aboveground C and peat C sink	Established but incomplete	[93,111]
Stop fertiliser applications	Reducing external nitrogen inputs reduces nutrient content and slows decomposition and C losses	Established but incomplete	[107]

of peatland management actions globally. We propose that the three-peat challenge offers a novel approach to assess the benefits and tradeoffs for C management from different types of intervention and to better comprehend the choices facing policymakers and land managers in determining future management trajectories.

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Data availability statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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