The potential of peatlands as nature-based climate solutions

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Revision submitted to Current Climate Change Reports (invited)
Keywords: carbon cycling, natural climate solutions, restoration, rewetting, wetlands

Abstract

Purpose of Review

Despite covering only 3% of the land surface, peatlands represent the largest terrestrial organic carbon stock on the planet and continue to act as a carbon sink. Managing ecosystems to reduce greenhouse gas (GHG) emissions and protect carbon stocks provide nature-based climate solutions that can play an important role in emission reduction strategies, particularly over the next decade. This review provides an overview of peatland management pathways that can contribute to natural climate solutions and compiles regional and global estimates for the size of potential GHG emission reductions.

Recent Findings

Degraded peatlands may account for 5% of current anthropogenic GHG emissions and therefore reducing emissions through rewetting and restoration offer substantial emission reductions. However, as a majority of peatland remains intact, particularly in boreal and subarctic regions, protection from future development is also an important peatland management pathway. Literature compilation indicates a global potential for peatland nature-based climate solutions of 1.1 to 2.6 Gt CO_2e yr^{-1} in 2030.

Summary

Peatland management can play an important role in GHG emission reductions while also providing many additional co-benefits such as biodiversity protection, reduced land subsidence and fire-severity mitigation. Yet, climate warming will hinder the ability of peatland ecosystems to continue to act as carbon sinks indicating the importance of reducing future warming through rapid decarbonization of the economy to protect these globally significant carbon stocks.

Introduction

Peatlands are wetland ecosystems with thick layers of partially-decomposed organic matter stored in their soils. Peatlands cover ~ 400 million hectares (Mha), about 3% of the earth's land area, yet are estimated to store up to 30% of all soil carbon with current estimates of over 600 Gt (Yu et al. 2010, Leifeld and Menichetti 2018, Nichols and Peteet 2019). This makes peatlands the largest terrestrial organic carbon stock, the protection of which is critical to mitigating climate change. Undisturbed peatlands are large, persistent carbon sinks. For example, northern peatland take up 360 ± 70 Mt of CO_2 per year and have a net cooling effect on the climate despite emissions of methane (CH_4) of 35 ± 3 Mt CH_4 yr^{-1} (Frolking & Roulet 2007, Hugelius et al. 2020. A history of land-use on peatlands has resulted in large areas of peat that are degrading and may account for emissions of 1.9 Gt CO_2e, 5% of current anthropogenic greenhouse gas (GHG) emissions (IUCN, 2021). This review paper explores the global potential for GHG emission reductions through peatland conservation and management.

Under the Paris Agreement global leadership committed to increasingly ambitious action to reduce GHG emissions to limit global warming. This will require rapid reduction in fossil fuel use but will likely also involve additional activities to reduce emissions and/or remove GHG from the atmosphere (Fuss et al. 2020). Nature-based climate solutions (NbS) have the potential to play an important role in GHG emission reductions and carbon dioxide (CO_2) removal, particularly in the near term (2021-2030) with an estimated global emission reduction of 23.8 Pg CO_2e yr^{-1} (Griscom et al. 2017) and their importance was discussed at the Conference of the Parties to the United Nations Framework Convention of Climate Change (UNFCCC) in the UK 2021 (COP26). NbS involve land management actions that reduce GHG emissions or result in GHG uptake. While specific actions depend on the system of interest, NbS generally arise from avoiding conversion of undeveloped (i.e., "natural" or "intact") areas, reducing the impact of disturbance on ecosystem GHG emissions through better management (i.e., sustainable ecosystem management), and ecological restoration.

As interest in NbS has continued to grow, calls for its careful application as part of a fulsome plan for climate action and sustainable development have arisen (Cohen-Shacham et al., 2016; Di Sacco et al., 2020). Seddon et al. (2021) outline four guidelines for successful application of NbS: 1) NbS cannot act as a substitute for rapid phase out of fossil fuels and should not be used to delay decarbonization of economies, 2) NbS should extend beyond tree-planting to incorporate a wide range of terrestrial and marine ecosystems, 3) there should be full engagement with local communities and Indigenous peoples when implementing NbS, and 4) NbS should also support, sustain or enhance biodiversity in addition to addressing climate change challenges. In addition to these guidelines, there is a need to ensure that NbS projects create long term protection of natural and restored ecosystems (i.e., carbon stored has permanence) and that efforts are made to avoid leakage of GHG emission reductions (e.g., where protection of ecosystems in one region lead to relocation of that disturbance to another location) (Anderegg, 2021). Here we explore peatland management actions that can reduce GHG emissions associated with these ecosystems and quantify the potential of peatland-based NbS globally. While NbS often play an important role in climate change adaptation strategies (Seddon et al. 2021), we focus here on peatland NbS for climate change mitigation through GHG emission reductions.

Peatland carbon storage and greenhouse gas exchange

Peatlands store carbon due to an imbalance between carbon uptake as photosynthesis and carbon losses as gases, CO_2 and CH_4, and with water outflows as dissolved and particulate organic carbon (Limpens et al. 2008). This imbalance occurs largely due to slow rates of decomposition in the anoxic conditions that develop in water saturated soils (Limpens et al. 2008). Recalcitrant substrate including *Sphagnum* mosses in many northern peatlands and lignin-rich woody material in the tropics, along with cool temperatures in northern peatlands, slow organic matter decomposition (Hodgkins et al. 2018). Although slow decomposition is generally seen as the driver of peat accumulation, longer growing seasons supporting higher plant productivity have been linked to periods of more rapid peat accumulation (Charman et al. 2015). Similarly, year-round growing seasons in the tropics that result in high levels of productivity also contribute to their net carbon sink function (Campbell et al. 2014).

When evaluating peatland-climate interactions, GHG exchange is important to consider along with carbon balance. Peatlands are net sinks for CO_2 but in terms of gross GHG produced in the soil, CO_2 is the gas produced in the largest quantity, mainly due to the respiration of microorganisms in the oxic part of the soil continuously breaking down organic matter (Vasander & Kettunen 2006). In the deeper anoxic regions, CH_4 is formed by Archaea (methanogenic microorganisms) by the utilization of a limited set of substrates – hydrogen and acetate being the most important (Segers 1998). Some of this CH_4 is also oxidized to CO_2 mainly above the water table in the uppermost layer of the peat by methanotrophic microorganisms (Lai 2009). The production of another GHG, nitrous oxide (N_2O), is linked to the microbial soil processes of nitrification and denitrification (Freeman et al. 1997, Augustin et al. 2011).

Although the natural processes in peatlands produce varying amounts of GHG - depending on the ecosystem’s condition, type, and location – most studies agree they are currently net carbon sinks on the global level (e.g., Kayranli et al. 2010). However, there are fears that anthropogenic and environmental factors could be altering the balance, turning peatlands into carbon sources (Ise et al. 2008). As carbon uptake by plant communities combined with waterlogged soils are the main drivers of carbon storage in peatland ecosystems, disruption of these factors is likely to result in loss of carbon sink function and net GHG emissions. Most peatland disturbances involve drainage, resulting in mineralization of stored organic matter and its release as CO_2. Clearing or harvesting of vegetation also reduces new carbon inputs to the system, while drainage of nutrient-rich peat soils and/or fertilization during agricultural use results in N_2O emissions (Anthony & Silver 2021). Induced GHG emissions can persist for decades to centuries as the peat deposit continues to decompose, even if primary disturbance activities have ceased (Waddington et al. 2002). Reinstating water-saturated conditions protects peat stocks from further mineralization resulting in substantial GHG emission reduction even if a net carbon sink is not recreated (Günther et al. 2020). Therefore, avoiding conversion of peatlands to other land-uses and rewetting already disturbed peatland represent the most promising pathways for peatland NbS.

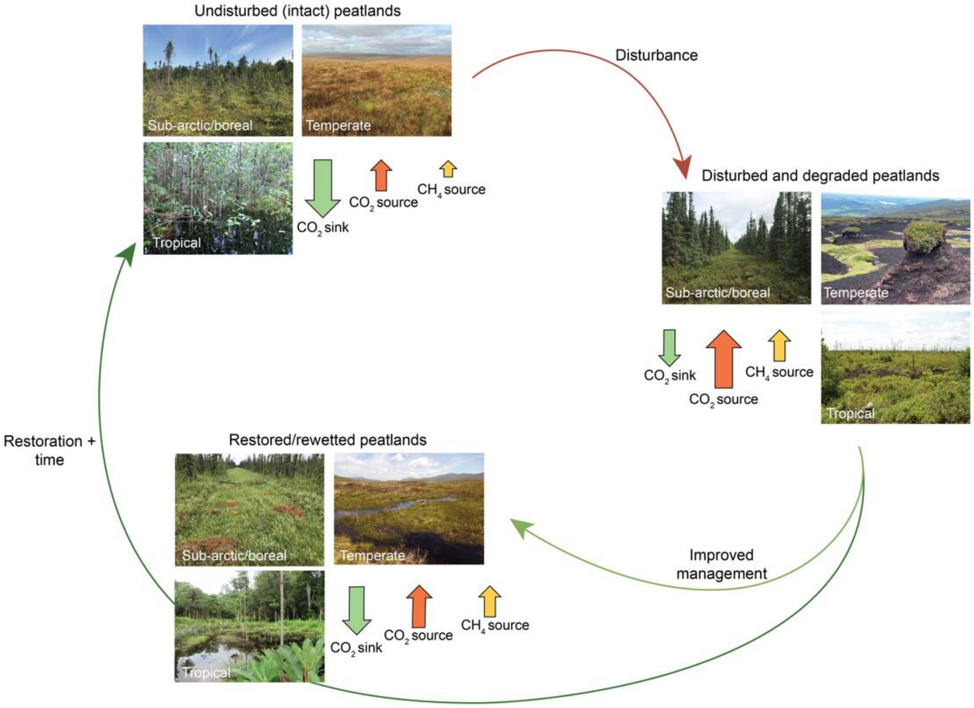

Figure 1. Conceptual diagram showing shifts in carbon and greenhouse gas exchange under various peatland uses. Red arrows indicate that the action results in an increase in GHG emissions and green arrows, a decrease in emissions. Dissolved organic carbon losses will result in an increase in off-site CO_2 emissions, included in the CO_2 source depicted here. Linked to the nature-based solution pathways discussed in the text, avoiding disturbance, improved management and restoration can all result in GHG emission reductions. Management actions can also result in shift in N_2O emissions (not shown in the diagram), but these are highly dependent on the type of peatland disturbed and the type of disturbance. Drainage of nutrient-rich peatlands and/or fertilization are likely to increase N_2O emissions. Photo credit: sub-arctic/boreal - Scott J. Davidson, temperate - Scott J. Davidson, Guaduneth Chico, tropical - Takashi Hirano.

Pathways for peatland NbS

Avoided conversion of peatland ecosystems

Although peatland disturbance occurs across the globe, at least 75% of peatlands remain in a relatively undisturbed state (Page & Baird 2016). Ongoing climate change will alter the rate of peatland carbon cycling but modelling indicates that northern peatlands will likely continue to act as carbon sinks or only very small sources to 2100 (Qiu et al. 2020; Müller & Joos 2021). Therefore, conserving undisturbed peatlands is critical to avoid additional GHG emissions. However, when considering NbS, the potential for emission reductions arises only in conservation of areas that would have otherwise been disturbed, with care taken to avoid leakage of disturbance to other jurisdictions.

Northern peatlands cover 320–400 Mha (Yu et al. 2010, Leifeld & Menichetti, 2018; Müller & Joos 2020) accounting for over 85% of global peatland area and ~80% of the peat carbon stock (Leifeld & Menichetti 2018). Despite drainage for forestry, agriculture, and resource development throughout North America, Europe and Russia, most boreal and subarctic peatlands remain undeveloped (Joosten, 2010, Leifeld & Menichetti, 2018). This suggests that the largest potential for NbS in this region arises from avoiding future land-use change. For example, Drever et al. (2021) estimated that up to 10.1 Mt of CO2e yr^{-1} could be saved through avoided peatland conversion in Canada by 2030, accounting for over 12% of total NbS potential for the country. In temperate regions many peatlands have been drained for human use, particularly for agriculture. Therefore, intact peatlands are less common in many European countries and temperate regions of North America (Leifeld & Menichetti 2018; Byun et al. 2018). Nonetheless, calls to protect remaining peat carbon stocks are widespread. For example, Ireland has 1.4 Mha of peatland area, of which at least 1.2 Mha have been disturbed for peat extraction or agriculture (Renou-Wilson 2018). While restoration of degraded peatland in Ireland will be an important part of climate action, the *Peatlands and Climate Change Action Plan 2030* acknowledges the importance of protecting all remaining peatlands in good condition to retain their ecosystem services, including carbon storage (O’Connell et al. 2021).

In the tropics, peatlands are distributed over 90–170 Mha, mainly in insular Southeast Asia (Indonesia and Malaysia), the upper Amazon (Peru and Brazil) and Congo Basin (the Republic of Congo and Democratic Republic of Congo) (Gumbricht et al. 2017; Ribeiro et al. 2021) with total peat carbon of 152-288 Gt (Ribeiro et al. 2021). Both area and carbon stock are currently estimated to be the largest in South America (Gumbricht et al. 2017). The estimates are significantly larger than previous ones (e.g., Page et al. 2011), mainly because vast peatlands were newly found in Amazonia (e.g., Draper et al. 2014) and the central Congo Basin (Dargie et al. 2017). Also, inconsistent peat definitions, different approaches for peat distribution, and difficulty in estimating peat depth result in the large uncertainties of peat area and carbon stock (Gumbricht et al., 2017; Ribeiro et al., 2021). Tropical peat is mainly made from woody materials. Its lower carbohydrate and greater aromatic content make it more recalcitrant than the *Sphagnum* peat typically found at higher latitudes (Hodgkins et al., 2018). The biomass of aboveground and belowground parts of relatively undisturbed peat forests were reported to average 169 and 37 t C ha^{-1}, respectively, in Southeast Asia (Verwer & van der Meer 2010). In addition, peat carbon stock is estimated to be about 4900 t C ha^{-1} in deep peatlands (peat depth > 3 m) in Indonesia (Warren et al. 2017); peat forests with peat depth > 3 m are designated not to be drained and not converted according to Indonesian law (Evers et al. 2017). Undisturbed peat swamp forest in Southeast Asia is a high carbon-density ecosystem, containing about 5000 t C ha^{-1} in total. Overall, protection of these dense tropical peatland carbon stocks by limiting drainage could help maintain 70 Gt of peat C in storage (Leifeld & Menichetti 2018)

Experts predict that peatland carbon emissions associated with land-use change from 2020–2100 will be 14 Gt C (-3 to 38 Gt C) for temperate, boreal and subarctic regions and 13 Gt C (-3 to 44 GtC) in the tropics (Loisel et al. 2020). Assuming a steady annual rate of disturbance, avoiding all this new peatland conversion (i.e., maximum potential) could amount to annual emission reduction of 305 Mt CO2e in 2030 (Table 1). Griscom et al. (2017) used global rates of disturbance and peatland emissions to estimate that annual greenhouse gas emissions could be reduced by 754 Mt CO_2e in 2030 through avoided peatland conversion during the period of 2020–2030 (Table 1).

Table 1. Potential peatland nature-based GHG emission reductions

Potential GHG emission reduction in 2030 (Mt CO_2e yr^{-1})[a]					
Tropical	*Temperate*	*Boreal*	*Global*	*Description*	*Ref*
		Avoided peatland conversion			
644	75	15	754 (237 to 1212)	Estimated based on rates of peatland conversion from Joosten (2010) and literature values of GHG emissions from disturbed peatlands	1
147 (-34 to 498)	158 (-34 to 430)		305 (-68 to 928)	Potential carbon emissions related to land-use change were estimated through expert assessment for the period 2020-2100. We assumed a constant rate of land-use change over time and recalculated annual emissions over the period to determine potential in 2030. Emitted carbon was converted to CO_2e assuming all was lost as CO_2.	2
		Mitigation[b]			
303 (219 to 411)	77 (65 to 90)	127 (106 to 149)	508 (390 to 650)	Estimated assuming that all peatland croplands and grasslands were managed with a water table half as deep as current drainage conditions. Potential reduction in N_2O emissions from rewetting not included.	3
		Restoration[b]			
497	267	51	815 (705 to 2471)	Estimated assuming all degraded peatland areas are restored using literature values for soil carbon sequestration rates and biomass growth	1
458 (356 to 652)	122 (118 to 126)	203 (176 to 230)	801 (650 to 1009)	Estimated for all grassland and cropland on peatland assuming complete rewetting. Potential reduction in N_2O emissions from rewetting not included.	3
1480 (40 to 2790)	160 (100 to 210)	260 (160 to 360)	1900 (310 to 3380)	Estimated assuming that all current GHG emissions from degraded peatlands could be avoided through restoration	4

a. Positive values indicate reductions in GHG emissions while negative values indicate potential for enhanced GHG emissions. Ranges are given when they were listed in the original publication.

b. Since the mitigation estimate arises from actions on lands that are also considered in the restoration estimates, these values should not be summed if considering a total NbS potential

1. Griscom et al. 2017
2. Loisel et al. 2020
3. Evans et al. 2021
4. Leifeld & Menichetti 2018

Mitigating GHG emissions associated with peatland disturbance

In areas where livelihoods are tightly tied to peatland utilization, complete avoidance of disturbance or restoration to conditions similar to undisturbed peatland ecosystems is likely not practical or desirable. Yet, changing management practices can contribute to substantial GHG emission reductions. The most widely applied and studied is paludiculture, the production of crops on wet soils, although other management options to reduce peatland GHG emissions are now also being explored.

Paludiculture

As many peatlands have been drained for agriculture, paludiculture is gaining attention as a climate change mitigation strategy (Wichtmann et al. 2016, Tan et al. 2021). In their review of the potential for paludiculture as a sustainable land-use for tropical peatlands, Tan et al. (2021) highlight that the term has been used in literature to refer to biomass production on peatland under a range of hydrological conditions ranging from rewetted systems, where the stored peat carbon is protected by high water tables, to systems that retain some extent of drainage and may continue to act as sources of carbon to the atmosphere. In either situation, the types of biomass that can be produced under wet soil conditions are generally alternatives to those produced under traditional agricultural systems. In temperate peatlands, production of *Sphagnum* fiber for horticultural use, reeds and rushes for animal fodder and construction materials, and willows or reeds for biofuel are some of the systems tested to date (Abel et al. 2013). In tropical peatlands, production of native peat swamp forest species in combination with other commodities including rubber, horticultural plants, and fruits and vegetables could be options (Yuwati et al. 2021). In all cases, the economic viability of the produced biomass may be a barrier to paludiculture adoption (Ziegler et al. 2021).

Field trials have observed clear GHG emission reductions in paludiculture systems (e.g., Günther et al. 2014, Knox et al. 2015, Table 2). Greater emission reductions can be achieved when the water table is kept closer to the surface (Karki et al. 2014) but any reduction in drainage depth likely results in some level of emission reductions. For example, Lestari et al. (2022) report a 17–18% reduction in soil GHG emissions from oil palm and rubber plantations (Table 2) following rewetting despite the water table remaining 40–100 cm below the surface. Evans et al. (2021) observed a strong linear relationship between peatland CO_2 emissions and water table across a range of undisturbed and drained peatlands. Accounting for the increase in CH_4 emissions that will occur under shallower water table, they determined a potential to reduce GHG emissions by 508 (390 - 650) Gt CO_2e (Table 1) if all peatlands currently drained globally for cropland and grassland had the extent of drainage reduced by half (i.e., the water table is raised halfway to the surface from its current depth). Approximately 60% of these emission reductions would arise from temperate peatlands with an additional 25% in the tropics, illustrating the distribution of current peatland agricultural use. Nitrous oxide emissions will also contribute to the GHG balance of many paludiculture sites and were not included in the analysis by Evans et al. (2021). However, raising the water level often reduces N_2O emissions as well (Karki et al. 2014, Hu et al. 2017), likely providing additional GHG emission reductions.

Table 2: Greenhouse gas fluxes and carbon exchange in some examples of peatland disturbance, rewetting and restoration

Peatland type	Land-use	CO$_2$ flux[a] (g CO$_2$ m^{-2} yr^{-1})	CH$_4$ flux[a] (g CH$_4$ m^{-2} yr^{-1})	Fluvial C export (gC m^{-2} yr^{-1})	N$_2$O flux[a] (g N$_2$O m^{-2} yr^{-1})	Reference
Tropical peat swamp forest	Intact forest	482[b]	25[b]		0.08	Azizan et al. 2021
	Recovering forest	680[b]	12[b]		0.29	
	Drained, Oil palm plantation	727[b]	1.1[b]		0.42	
Tropical peat swamp forest	Intact	1550 ± 880	7.3 ± 3.1	30 ± 10	0.02 ± 0.02	Deshmukh et al. 2021
	Drained	3980 ± 290	4.3 ± 1.1	50 ± 10	0.11 ± 0.06	
Tropical peat swamp forest	Drained, reforested	4968 ± 684[b]	-0.88 ± 57[b,c]		3.5 ± 7.4[c]	Lestari et al. 2022
	Drained, Oil palm	5571 ± 554[b]	3.0 ± 29 [b,c]		15 ± 12 [c]	
	Drained, Rubber plantation	6136 ± 728[b]	-1.7 ± 33 [b,c]		64 ± 20 [c]	
	Rewetted, reforested	4518 ± 202[b]	70 ± 29 [b,c]		-1.8 ± 4.6 [c]	
	Rewetted oil palm	4249 ± 318[b]	47 ± 76 [b,c]		-3.9 ± 13 [c]	
	Rewetted rubber	4184 ± 231[b]	30 ± 69 [b,c]		41 ± 20 [c]	
Warm temperate drained peat	Drained, pasture	1250 ± 268	7.8 ± 2.0 (15 ± 3.5)[d]			Knox et al. 2015
	Drained, corn	2093 ± 271	n/a			
	Rewetted, rice	410 ± 278	7.1 ± 1.1			
	Restored wetland	-1349 ± 169	71 ± 1.0			
	Restored wetland	-1455 ± 73	52 ± 1.5			
Nutrient poor peat grassland	Shallow drained, grazed	282 (234 – 330)	1.6 (1.1 – 2)			Renou-Wilson et al. 2016
	Shallow drained, ungrazed	297 (279-319)	1.9 (1.4 – 2.5)			
	Rewetted, grazed	312 (312-315)	12 (12-13)			
	Rewetted, ungrazed	-147 (-293 – 2.9)	5.9 (4.5 – 7.2)			
Temperate raised bog	Drained, milled peat extraction	115 ± 11	0			Renou-Wilson et al. 2019
	Drained, domestic peat extraction	137 ± 24	0.77 ± 0.49			
	Rewetted milled peat	66 ± 168	5.0 ± 2.2			
	Rewetted drained	-49 ± 68	19 ± 5			
Temperate blanket bog	Drained, milled peat extraction	506 ± 40	0			Wilson et al. 2016
	Drained, peat extraction, revegetated (Juncus)	154 ± 84	0			
	Rewetted, bare	209 ± 110	0.1			
	Rewetted, revegetated (Juncus)	-271 ± 246	11.6 ± 10.7			
	Rewetted, revegetated (Eriophorum)	-308 ± 378	14.9 ± 12			
	Rewetted, revegetated (Sphagnum/Erioph.)	-953 ±656	7.1 ± 4			
Temperate/ boreal bog	Intact	-268 (-33 - -499)	8 (3-13)	17 (14-20)		Nugent et al. 2019
	Drained, vacuum-extracted	1631 (1562-1686)	0.7 (0.4-0.9)	35 (26-45)		
	Drained, vaccum-extracted, unrestored 15 yr	792 (484-1100)	0.7 (0.4-0.9)	35 (26-45)		
	Restored, 1 yr	1848 (1067-2629)	1.5 (0.7-2.3)			
	Restored, 4 yr	532 (-44-1107)	5.7 (0.9-10.5)			
	Restored, 15 yr	-330 (-403-253)	5.9 (5.6-6.0)	8 (6-10)		

a. Negative values indicate uptake by the ecosystem
b. Soil fluxes only
c. Annual values calculated from stated mean hourly values by multiplying by 24 hours x 365 days.
d. Methane emissions measured in 2 different conditions and both reported in the paper.

Other management practices with the potential to reduce peatland GHG emissions

In addition to reduced peatland drainage to protect soil carbon stocks, best management practices may also contribute to GHG emission reductions around industrial disturbances. However, for most examples, data on actual GHG emission reductions achieved is lacking or collected from only a few case studies. Therefore, the potential for GHG emission reductions at regional to global scales remains unclear (Wilkinson et al., in press).

In peat-rich regions where development occurs, infrastructure associated with industry or urban expansion will result in peatland loss and can affect the function of the remaining peatlands adjacent to the disturbance. For example, Saraswati & Strack (2019) determined that hydrologic changes that occur due to peatland road-crossings result in measurable increases in CH_4 emissions from the adjacent peatland. These impacts arise from a damming effect caused by the blockage of water flow by the road where flooding on the upgradient side of the road results in enhanced CH_4 production and emissions that were not compensated by the small emission reductions measured on the drier downgradient side. However, this development-induced increase in CH_4 emissions was reduced by at least half when culverts were in place to improve water flow and reduce impoundment (Saraswati & Strack 2019). Applying best management practices during peat extraction, geologic exploration, forestry, and energy development projects (e.g., oil well-pads and wind farms) could likely also lead to GHG emission reductions. Unfortunately, we know little about the fate of peat carbon under these disturbances, the appropriate management practices to apply, or the resulting GHG emissions reductions, making quantification of these actions as potential NbS impossible at this time. As it is unlikely that all development of peatland areas can be avoided, determining mechanisms to best protect peatland carbon stocks require further study.

In addition to minimizing peatland disturbance, interest is also growing in management actions that could enhance or protect carbon storage in relatively intact peatlands. While many peatland ecosystems will likely continue to act as carbon sinks over the next century (Qiu et al. 2020), climate change will alter disturbance regimes, enhancing permafrost thaw, fire frequency and severity, and periods of drought and/or flooding, resulting in emission of stored peat carbon (Turetsky et al. 2015, Hugelius et al. 2020, Loisel et al. 2020). While the best way to avoid the effects of these climate change-induced disturbances is to limit warming through rapid reduction in GHG emissions, land management options have also been discussed that could reduce carbon losses. For example, fuel management treatments have been tested in boreal peatlands in an attempt to reduce wildfire severity, limiting release of peat carbon through combustion (Wilkinson et al. 2018). Initial trials under a controlled burn observed a reduced depth of burn under a canopy thinning treatment but shifts in peat bulk density and availability of fine fuels resulted in greater carbon losses than control, untreated areas (Wilkinson et al. 2018); however, tests under a wider range of conditions are needed. Given the extensive and growing area of peatland affected by wildfire annual (Turetsky et al. 2015), the potential for emission reductions from fuel management could be large; however, the feasibility of deployment and its ability to effectively reduce peat carbon losses has yet to be clearly demonstrated and quantified.

Shifts in management of animal populations may also contribute to the protection of stored peat carbon. Experiments are underway in Siberia to reintroduce large herbivores to reduce snowpack insulation and retain permafrost (Beer et al. 2020). Early results indicate that grazing reduces CH_4 emissions but may actually result in soil warming and drying that could accelerate soil C losses (Fischer et al. 2022). Longer term studies are required to assess whether this management action will lead to GHG emission reductions. Finally, beaver activity in and around peatlands can maintain high water levels (Karran et al. 2018) that result in greater annual net ecosystem CO_2 uptake (He et al. 2021) and effectively rewet previously drained peatlands (Minke et al. 2020). Thus, while beaver dams are often cleared by land managers to alleviate flooding, maintenance of beaver populations and the resulting dams could be another NbS strategy to enhance peatland carbon uptake and storage.

Restoration and rewetting of peatland ecosystems

Ecological restoration is defined as “the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed” (Gann et al. 2019). Actions to promote peatland recovery have been applied in many regions, in which the main goal is to re-wet these landscapes to bring back suitable hydrological conditions needed to support carbon sequestration and avoid further carbon flux losses (Evans et al. 2021). Under drained conditions, peat carbon stocks are also highly vulnerable to combustion during wildfire, with potential for globally significant emissions (Huijnen et al. 2016). For example, peat fires in Indonesia in 1997 released 0.8 to 2.6 Gt C, an amount equivalent to 13 - 40% of annual carbon emissions in that year (Page et al. 2002). Therefore, rewetting drained peatlands has the added benefit of reduced GHG emissions from peatland wildfire (Granath et al. 2016). Effective restoration of disturbed peatlands needs four Rs, consisting of rewetting, revegetation (reforestation in tropical peat swamp forests), revitalization of livelihood and reducing fires, of which rewetting and accompanying reducing fires have the highest priority (Harrison et al. 2019).

At the ecosystem scale, GHG emission reductions associated with rewetting and restoration have been demonstrated in a range of temperate and boreal peatland types and following a variety of disturbances Application of the moss layer transfer technique in Canada resulted in the return of an annual net carbon sink of 78 ± 17 g C m^{-2} yr^{-1} to a bog following horticultural peat extraction by 15 years post-restoration (Nugent et al. 2018). The return of CO_2 uptake post-restoration was also observed at restored cutover peatlands in Ireland and Estonia, although accompanied by an increase in CH_4 emissions (Jarveoja et al. 2016; Renou-Wilson et al. 2019). Rewetting agricultural peatlands in California converted sites from sources of up to 1250 g CO_2 m^{-2} yr^{-1} and 15 g CH_4 m^{-2} yr^{-1}, to a CO_2 sink of up to 1455 g CO_2 m^{-2} yr^{-1} with an increase in CH_4 emissions to 52–71 g CH_4 m^{-2} yr^{-1} (Knox et al. 2015, Table 2). Similarly, rewetting of agricultural peatlands in Germany led to GHG emission reductions that were enhanced by removal of nutrient rich topsoil and introduction of *Sphagnum* moss (Huth et al. 2021). Although concerns have been raised regarding the higher CH_4 emissions that occur due to shallow water table following restoration, these are offset by substantial reductions in CO_2 emissions and the protection of the remaining peatland carbon stock (Günther et al. 2020). Preventing ongoing mineralization of existing peat carbon provides the greatest climate benefits leading to calls for rapid implementation of restoration programs (Nugent et al. 2019; Günther et al. 2020).

In tropical peatland the soil water regime is one of the most important factors for controlling the carbon balance (e.g., Hirano et al. 2014). It has been reported that soil heterotrophic respiration or peat decomposition negatively correlated to ground water level (GWL). Their linear relationship indicates that every 10 cm rise of GWL reduced CO_2 emission by 3.7 t CO_2 ha^{-1} yr^{-1} in a burned degraded peatlands (Hirano et al. 2014) and 7.3 t CO_2 ha^{-1} yr^{-1} in a rubber plantation on drained peat (Wakhid et al. 2017) in

Central Kalimantan, Indonesia. As for ecosystem scale CO_2 balance, every 10 cm rise of minimum monthly-mean GWL, which is usually measured in the late dry season, reduced net CO_2 emission by 1.8 t CO_2 ha^{-1} yr^{-1} in peat swamp forests (Hirano et al. 2016). In contrast, as observed in northern peatlands, CH_4 emissions both on the peat surface (Ishikura et al. 2019) and above peat forest (Wong et al. 2020) increased exponentially with GWL until it rises to the ground level. For instance, 10 cm rise of GWL from -30 cm increased ecosystem-scale CH_4 emission by 0.46 t CO_2e ha^{-1} yr^{-1} (Wong et al. 2020), considering the global warming potential (GWP) of CH_4 of 34 over a timescale of 100 years (IPCC 2013). Thus, the rewetting effect of reducing CO_2 emission would be offset to some extent by increasing CH_4 emission in the condition of relatively high GWL but still provides net GHG mitigation (Evans et al. 2021).

It is important to note that there is a transition period following restoration activities when GHG emissions can be elevated or at least the peatland remains a source of carbon to the atmosphere as plants become established (Nugent et al. 2019). Further, long term studies that monitor GHG emissions in peatlands for over a decade remain rare (e.g., Wilson et al. 2016, Nugent et al. 2018) making the definition of this transition period uncertain. Therefore, restoration actions must be seen as an investment towards longer term climate change mitigation (e.g., Drever et al. 2021). Further, global estimates of the potential for GHG emissions reductions for peatland restoration generally assume that all degraded peatland areas are restored even though this may not be possible in practice suggesting these represent a high end of potential emission reductions. With these considerations in mind, current global estimates for GHG emission reductions related to peatland restoration range from 800 to 1900 Mt CO_2e in 2030 (Table 1).

Challenges and co-benefits associated with peatland NbS

The importance of protecting peatland carbon as part of climate change mitigation strategies is gaining global attention (UNEP 2016), yet application of peatland NbS remains challenging. Managing peatlands for carbon storage and GHG emission reductions requires tradeoffs with economic benefits and, in some cases, other ecosystem services (Juutinen et al. 2021). Thus, willingness to implement peatland management actions to reduce GHG emissions will depend on perceived balance between benefits and costs, that will be stakeholder and context dependent (van Noordwijk et al. 2014, Buschmann et al. 2020). The continued high level of uncertainty in estimates of actual GHG emission reductions from peatland management actions adds to this challenge (e.g., van Noordwijk et al. 2014). Policy from local to global levels is required to promote climate-friendly peatland management but may not achieve desired outcomes. For example, in 2011 Indonesia implemented a moratorium on new forest concession licenses for palm oil, timber and logging and reported GHG emission reductions of 11.2 Mt CO_2-e in 2017 due to avoided deforestation and degradation (Groom et al. 2022). This action was partially supported by economic incentives through the United Nations program Reducing Emissions from Deforestation and Degradation (REDD+); Norway agreed to pay Indonesia USD $56.2 million, based on a carbon price of USD $5 tCO2-$e^{-1}$ (Groom et al. 2022). However, recent evaluation of the program indicates that, despite the moratorium, no reduction in peatland forest loss was detected compared to projected rates, suggesting that the program was ineffective in avoid disturbance and reducing GHG emissions (Groom et al. 2022). This indicates that effective peatland management for GHG emission reduction requires interdisciplinary and multi-stakeholder collaboration that promotes iterative evaluation of policy and actions as new information becomes available. The involvement of local communities adds to the challenge of collaboration across an often-diverse group of stakeholders but is critical for peatland management (Mishra et al. 2021). Although the global motivation for peatland restoration is to reduce carbon emission, local stakeholders require direct benefit from peatlands. Since many people are living in and around peatlands, particularly in temperate and tropical regions, it is indispensable for local people to participate in the activities at all stages.

Moreover, ongoing climate change will pose challenges due to altered water resource availability, the occurrence of extreme events, and shifting land-use pressures that may create competing priorities for land and resources needed for peatland NbS pathways. For example, water availability is necessary for peatland rewetting projects. Although this may not be an issue for many peatlands, changing precipitation patterns, local hydrologic conditions and/or sea level rise may limit the availability of water of suitable quality at the appropriate times of year for rewetting activities (Acreman et al. 2007). Demands for future food production will likely also place limits on the extent of peatland restoration and/or shifts to paludiculture (Tan et al. 2021). Further, studies suggest demand for horticultural peat will continue to expand to meet rising greenhouse-based food production providing additional pressure for peat extraction if alternative growing media cannot meet the demand (Blok et al. 2019). Northward expansion of resource extraction will continue to put pressure on boreal and subarctic peatlands, requiring policy mechanisms that support long term peatland conservation to avoid conversion and the associated GHG emissions (Harris et al. 2021). Even when protected from development, climate change-induced disturbance also places peatland C stocks at risk and this needs to be accounted for when including peatland NbS in climate change mitigation strategies (Coffield et al. 2021).

Despite the challenges involved with using peatlands as a NbS, the avoided conversion, better management and restoration of peatlands provides a vast array of co-benefits. These include flood management and maintenance of water quality (Ritson et al. 2016), reduced land subsidence (Knox et al. 2015), fire risk management (Granath et al. 2016) and human well-being (IUCN, 2018). For example, when in good condition, peatlands can not only provide mitigation to regional climate warming (Helbig et al. 2020), acting as cool humid islands on the landscape due to the wet conditions found there (Worrall et al. 2020) but also have greater resilience to a number of climatic changes including wildfire (Kettridge et al. 2017, Taufik et al. 2022). A reduction in peat fires will also have direct positive human health and economic benefits through by reducing property loss and the frequency and severity of haze events (Hu et al. 2018). Peatlands globally provide habitat for rare and endangered species such as the woodland caribou (*Rangifer tarandus caribou*) (Barber et al. 2018) and the orangutan (*Pongo pygmaeus*) (Felton et al. 2003). Furthermore, the rewetting and restoration of peatlands can re-establish ecological diverse plant communities (Renou-Wilson et al. 2019). The restoration of degraded peatland habitats can not only prevent further decline of endangered species but could also enhance overall biodiversity. Finally, maintenance of intact peatlands also protects the land-base for many Indigenous communities globally, who use peatland landscapes in a variety of ways, including for subsistence hunting and food foraging (David Suzuki Foundation, 2013).

Conclusions

Globally, peatland ecosystems represent the largest terrestrial organic C stock with at least 600 Gt of stored carbon. Preventing its release to the atmosphere can play an important role in slowing anthropogenic climate change. A combination of avoiding future peatland conversion and mitigation or halting release of carbon from currently disturbed peatlands through rewetting and restoration has the potential to contribute a reduction in GHG emissions of 1.1 to 2.6 Gt CO_2e yr^{-1} in 2030 (Table 1). In order to achieve these emission reductions, policies from local to international levels are needed to protect carbon sink function in the majority of currently undeveloped, intact peatlands and support rewetting of those currently drained (Moomaw et al. 2018). Effective implementation will require collaboration across levels of government, with industrial and agricultural land-users, and with local communities and Indigenous peoples that depend on peatlands for livelihoods and traditional use. Ongoing climate warming continues to pose additional threats to peatland carbon stocks due to increased decomposition under warmer temperatures and drought, wildfires, and permafrost thaw. Therefore, gaining benefits from peatlands as NbS also requires rapid reduction in fossil fuel GHG emissions to limit warming and provide the best chance to maintain these ecosystems within suitable conditions for maintenance of net carbon sink function into the future.

Acknowledgements

Indigenous peoples around the world play critical roles in peatland stewardship. We acknowledge that much of this paper was written at the University of Waterloo situated on the traditional and unceded territory of the Attawandaron, Anishinaabeg and Haudenosaunee peoples.

MS in a Natural Sciences and Engineering Research Council (NSERC) Canada Research Chair with this work also supported by an NSERC Discovery Grant. TH was supported by JSPS KAKENHI Grant Number 19H05666. We thank Nataša Popović for help with the creation of Figure 1. Comments from the handling editor, J. Melton, and 2 anonymous reviewers improved the manuscript.

Conflict of Interest Statement

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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