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1 The potential of peatlands as nature-based 2 climate solutions

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17 Abstract

18 *Purpose of Review*

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

25 *Recent Findings*

26 Degraded peatlands may account for 5% of current anthropogenic GHG emissions and therefore reducing
27 emissions through rewetting and restoration offer substantial emission reductions. However, as a majority
28 of peatland remains intact, particularly in boreal and subarctic regions, protection from future
29 development is also an important peatland management pathway. Literature compilation indicates a
30 global potential for peatland nature-based climate solutions of 1.1 to 2.6 Gt CO₂e yr⁻¹ in 2030.

31 *Summary*

32 Peatland management can play an important role in GHG emission reductions while also providing many
33 additional co-benefits such as biodiversity protection, reduced land subsidence and fire-severity
34 mitigation. Yet, climate warming will hinder the ability of peatland ecosystems to continue to act as

35 carbon sinks indicating the importance of reducing future warming through rapid decarbonization of the
36 economy to protect these globally significant carbon stocks.

37 Introduction

38 Peatlands are wetland ecosystems with thick layers of partially-decomposed organic matter stored in their
39 soils. Peatlands cover ~ 400 million hectares (Mha), about 3% of the earth's land area, yet are estimated
40 to store up to 30% of all soil carbon with current estimates of over 600 Gt (Yu et al. 2010, Leifeld and
41 Menichetti 2018, Nichols and Peteet 2019). This makes peatlands the largest terrestrial organic carbon
42 stock, the protection of which is critical to mitigating climate change. Undisturbed peatlands are large,
43 persistent carbon sinks. For example, northern peatland take up 360 ± 70 Mt of CO₂ per year and have a
44 net cooling effect on the climate despite emissions of methane (CH₄) of 35 ± 3 Mt CH₄ yr⁻¹ (Frolking &
45 Roulet 2007, Hugelius et al. 2020). A history of land-use on peatlands has resulted in large areas of peat
46 that are degrading and may account for emissions of 1.9 Gt CO₂e, 5% of current anthropogenic
47 greenhouse gas (GHG) emissions (IUCN, 2021). This review paper explores the global potential for GHG
48 emission reductions through peatland conservation and management.

49
50 Under the Paris Agreement global leadership committed to increasingly ambitious action to reduce GHG
51 emissions to limit global warming. This will require rapid reduction in fossil fuel use but will likely also
52 involve additional activities to reduce emissions and/or remove GHG from the atmosphere (Fuss et al.
53 2020). Nature-based climate solutions (NbS) have the potential to play an important role in GHG
54 emission reductions and carbon dioxide (CO₂) removal, particularly in the near term (2021-2030) with an
55 estimated global emission reduction of 23.8 Pg CO₂e yr⁻¹ (Griscom et al. 2017) and their importance was
56 discussed at the Conference of the Parties to the United Nations Framework Convention of Climate
57 Change (UNFCCC) in the UK 2021 (COP26). NbS involve land management actions that reduce GHG
58 emissions or result in GHG uptake. While specific actions depend on the system of interest, NbS
59 generally arise from avoiding conversion of undeveloped (i.e., "natural" or "intact") areas, reducing the
60 impact of disturbance on ecosystem GHG emissions through better management (i.e., sustainable
61 ecosystem management), and ecological restoration.

62
63 As interest in NbS has continued to grow, calls for its careful application as part of a fulsome plan for
64 climate action and sustainable development have arisen (Cohen-Shacham et al., 2016; Di Sacco et al.,
65 2020). Seddon et al. (2021) outline four guidelines for successful application of NbS: 1) NbS cannot act
66 as a substitute for rapid phase out of fossil fuels and should not be used to delay decarbonization of
67 economies, 2) NbS should extend beyond tree-planting to incorporate a wide range of terrestrial and
68 marine ecosystems, 3) there should be full engagement with local communities and Indigenous peoples
69 when implementing NbS, and 4) NbS should also support, sustain or enhance biodiversity in addition to
70 addressing climate change challenges. In addition to these guidelines, there is a need to ensure that NbS
71 projects create long term protection of natural and restored ecosystems (i.e., carbon stored has
72 permanence) and that efforts are made to avoid leakage of GHG emission reductions (e.g., where
73 protection of ecosystems in one region lead to relocation of that disturbance to another location)
74 (Anderegg, 2021). Here we explore peatland management actions that can reduce GHG emissions
75 associated with these ecosystems and quantify the potential of peatland-based NbS globally. While NbS

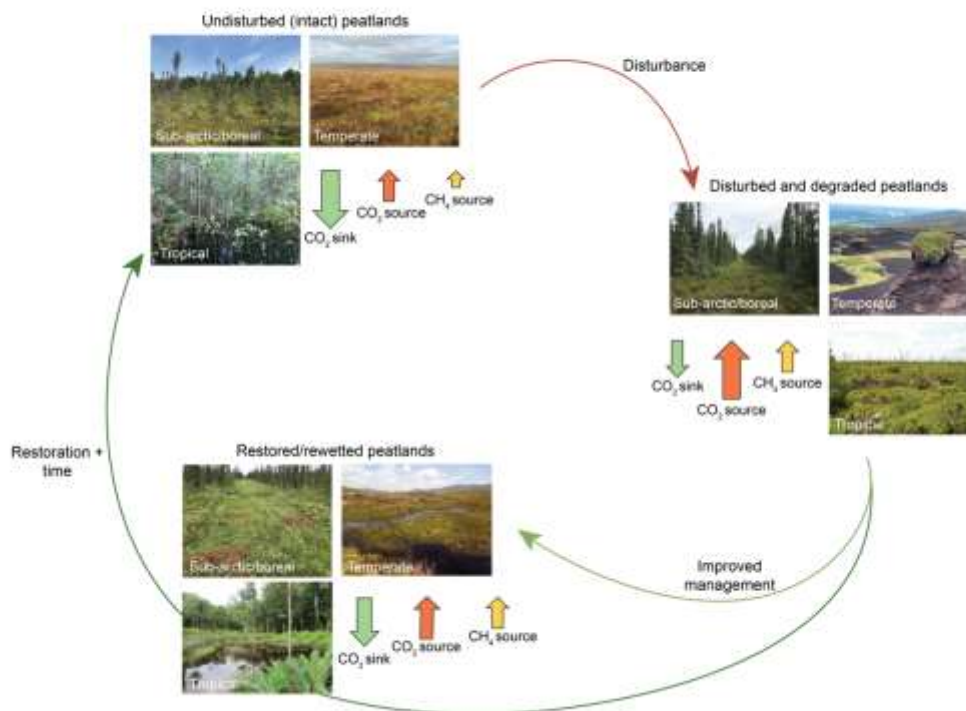
76 often play an important role in climate change adaptation strategies (Seddon et al. 2021), we focus here
77 on peatland NbS for climate change mitigation through GHG emission reductions.

78 Peatland carbon storage and greenhouse gas exchange

79 Peatlands store carbon due to an imbalance between carbon uptake as photosynthesis and carbon losses as
80 gases, CO₂ and CH₄, and with water outflows as dissolved and particulate organic carbon (Limpens et al.
81 2008). This imbalance occurs largely due to slow rates of decomposition in the anoxic conditions that
82 develop in water saturated soils (Limpens et al. 2008). Recalcitrant substrate including *Sphagnum* mosses
83 in many northern peatlands and lignin-rich woody material in the tropics, along with cool temperatures in
84 northern peatlands, slow organic matter decomposition (Hodgkins et al. 2018). Although slow
85 decomposition is generally seen as the driver of peat accumulation, longer growing seasons supporting
86 higher plant productivity have been linked to periods of more rapid peat accumulation (Charman et al.
87 2015). Similarly, year-round growing seasons in the tropics that result in high levels of productivity also
88 contribute to their net carbon sink function (Campbell et al. 2014).

89
90 When evaluating peatland-climate interactions, GHG exchange is important to consider along with carbon
91 balance. Peatlands are net sinks for CO₂ but in terms of gross GHG produced in the soil, CO₂ is the gas
92 produced in the largest quantity, mainly due to the respiration of microorganisms in the oxic part of the
93 soil continuously breaking down organic matter (Vasander & Kettunen 2006). In the deeper anoxic
94 regions, CH₄ is formed by Archaea (methanogenic microorganisms) by the utilization of a limited set of
95 substrates – hydrogen and acetate being the most important (Segers 1998). Some of this CH₄ is also
96 oxidized to CO₂ mainly above the water table in the uppermost layer of the peat by methanotrophic
97 microorganisms (Lai 2009). The production of another GHG, nitrous oxide (N₂O), is linked to the
98 microbial soil processes of nitrification and denitrification (Freeman et al. 1997, Augustin et al. 2011).

99
100 Although the natural processes in peatlands produce varying amounts of GHG - depending on the
101 ecosystem's condition, type, and location – most studies agree they are currently net carbon sinks on the
102 global level (e.g., Kayranli et al. 2010). However, there are fears that anthropogenic and environmental
103 factors could be altering the balance, turning peatlands into carbon sources (Ise et al. 2008). As carbon
104 uptake by plant communities combined with waterlogged soils are the main drivers of carbon storage in
105 peatland ecosystems, disruption of these factors is likely to result in loss of carbon sink function and net
106 GHG emissions. Most peatland disturbances involve drainage, resulting in mineralization of stored
107 organic matter and its release as CO₂. Clearing or harvesting of vegetation also reduces new carbon inputs
108 to the system, while drainage of nutrient-rich peat soils and/or fertilization during agricultural use results
109 in N₂O emissions (Anthony & Silver 2021). Induced GHG emissions can persist for decades to centuries
110 as the peat deposit continues to decompose, even if primary disturbance activities have ceased
111 (Waddington et al. 2002). Reinstating water-saturated conditions protects peat stocks from further
112 mineralization resulting in substantial GHG emission reduction even if a net carbon sink is not recreated
113 (Günther et al. 2020). Therefore, avoiding conversion of peatlands to other land-uses and rewetting
114 already disturbed peatland represent the most promising pathways for peatland NbS.



115
 116 **Figure 1.** Conceptual diagram showing shifts in carbon and greenhouse gas exchange under various peatland uses.
 117 Red arrows indicate that the action results in an increase in GHG emissions and green arrows, a decrease in
 118 emissions. Dissolved organic carbon losses will result in an increase in off-site CO₂ emissions, included in the CO₂
 119 source depicted here. Linked to the nature-based solution pathways discussed in the text, avoiding disturbance,
 120 improved management and restoration can all result in GHG emission reductions. Management actions can also
 121 result in shift in N₂O emissions (not shown in the diagram), but these are highly dependent on the type of peatland
 122 disturbed and the type of disturbance. Drainage of nutrient-rich peatlands and/or fertilization are likely to increase
 123 N₂O emissions. Photo credit: sub-arctic/boreal - Scott J. Davidson, temperate - Scott J. Davidson, Guaduneth Chico,
 124 tropical - Takashi Hirano.

125 Pathways for peatland NbS

126 *Avoided conversion of peatland ecosystems*

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

134 Northern peatlands cover 320–400 Mha (Yu et al. 2010, Leifeld & Menichetti, 2018; Müller & Joos
135 2020) accounting for over 85% of global peatland area and ~80% of the peat carbon stock (Leifeld &
136 Menichetti 2018). Despite drainage for forestry, agriculture, and resource development throughout North
137 America, Europe and Russia, most boreal and subarctic peatlands remain undeveloped (Joosten, 2010,
138 Leifeld & Menichetti, 2018). This suggests that the largest potential for NbS in this region arises from
139 avoiding future land-use change. For example, Drever et al. (2021) estimated that up to 10.1 Mt of CO₂e
140 yr⁻¹ could be saved through avoided peatland conversion in Canada by 2030, accounting for over 12% of
141 total NbS potential for the country. In temperate regions many peatlands have been drained for human
142 use, particularly for agriculture. Therefore, intact peatlands are less common in many European countries
143 and temperate regions of North America (Leifeld & Menichetti 2018; Byun et al. 2018). Nonetheless,
144 calls to protect remaining peat carbon stocks are widespread. For example, Ireland has 1.4 Mha of
145 peatland area, of which at least 1.2 Mha have been disturbed for peat extraction or agriculture (Renou-
146 Wilson 2018). While restoration of degraded peatland in Ireland will be an important part of climate
147 action, the *Peatlands and Climate Change Action Plan 2030* acknowledges the importance of protecting
148 all remaining peatlands in good condition to retain their ecosystem services, including carbon storage
149 (O’Connell et al. 2021).

150
151 In the tropics, peatlands are distributed over 90–170 Mha, mainly in insular Southeast Asia (Indonesia
152 and Malaysia), the upper Amazon (Peru and Brazil) and Congo Basin (the Republic of Congo and
153 Democratic Republic of Congo) (Gumbrecht et al. 2017; Ribeiro et al. 2021) with total peat carbon of
154 152–288 Gt (Ribeiro et al. 2021). Both area and carbon stock are currently estimated to be the largest in
155 South America (Gumbrecht et al. 2017). The estimates are significantly larger than previous ones (e.g.,
156 Page et al. 2011), mainly because vast peatlands were newly found in Amazonia (e.g., Draper et al. 2014)
157 and the central Congo Basin (Dargie et al. 2017). Also, inconsistent peat definitions, different approaches
158 for peat distribution, and difficulty in estimating peat depth result in the large uncertainties of peat area
159 and carbon stock (Gumbrecht et al., 2017; Ribeiro et al., 2021). Tropical peat is mainly made from woody
160 materials. Its lower carbohydrate and greater aromatic content make it more recalcitrant than the
161 *Sphagnum* peat typically found at higher latitudes (Hodgkins et al., 2018). The biomass of aboveground
162 and belowground parts of relatively undisturbed peat forests were reported to average 169 and 37 t C ha⁻¹,
163 respectively, in Southeast Asia (Verwer & van der Meer 2010). In addition, peat carbon stock is estimated
164 to be about 4900 t C ha⁻¹ in deep peatlands (peat depth > 3 m) in Indonesia (Warren et al. 2017); peat
165 forests with peat depth > 3 m are designated not to be drained and not converted according to Indonesian
166 law (Evers et al. 2017). Undisturbed peat swamp forest in Southeast Asia is a high carbon-density
167 ecosystem, containing about 5000 t C ha⁻¹ in total. Overall, protection of these dense tropical peatland
168 carbon stocks by limiting drainage could help maintain 70 Gt of peat C in storage (Leifeld & Menichetti
169 2018)

170
171 Experts predict that peatland carbon emissions associated with land-use change from 2020–2100 will be
172 14 Gt C (-3 to 38 Gt C) for temperate, boreal and subarctic regions and 13 Gt C (-3 to 44 GtC) in the
173 tropics (Loisel et al. 2020). Assuming a steady annual rate of disturbance, avoiding all this new peatland
174 conversion (i.e., maximum potential) could amount to annual emission reduction of 305 Mt CO₂e in 2030
175 (Table 1). Griscorn et al. (2017) used global rates of disturbance and peatland emissions to estimate that
176 annual greenhouse gas emissions could be reduced by 754 Mt CO₂e in 2030 through avoided peatland
177 conversion during the period of 2020–2030 (Table 1).

178 **Table 1.** Potential peatland nature-based GHG emission reductions

Potential GHG emission reduction in 2030					
(Mt CO₂e yr⁻¹)^a					
<i>Tropical</i>	<i>Temperate</i>	<i>Boreal</i>	<i>Global</i>	<i>Description</i>	<i>Ref</i>
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 ₂ e 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 ₂ O 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 ₂ O 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

179
180 a. Positive values indicate reductions in GHG emissions while negative values indicate potential for
181 enhanced GHG emissions. Ranges are given when they were listed in the original publication.
182 b. Since the mitigation estimate arises from actions on lands that are also considered in the restoration
183 estimates, these values should not be summed if considering a total NbS potential
184 1. Griscom et al. 2017
185 2. Loisel et al. 2020
186 3. Evans et al. 2021
187 4. Leifeld & Menichetti 2018

188 *Mitigating GHG emissions associated with peatland disturbance*

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

194

195 Paludiculture

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

210

211 Field trials have observed clear GHG emission reductions in paludiculture systems (e.g., Günther et al.
212 2014, Knox et al. 2015, Table 2). Greater emission reductions can be achieved when the water table is
213 kept closer to the surface (Karki et al. 2014) but any reduction in drainage depth likely results in some
214 level of emission reductions. For example, Lestari et al. (2022) report a 17–18% reduction in soil GHG
215 emissions from oil palm and rubber plantations (Table 2) following rewetting despite the water table
216 remaining 40–100 cm below the surface. Evans et al. (2021) observed a strong linear relationship between
217 peatland CO₂ emissions and water table across a range of undisturbed and drained peatlands. Accounting
218 for the increase in CH₄ emissions that will occur under shallower water table, they determined a potential
219 to reduce GHG emissions by 508 (390 - 650) Gt CO₂e (Table 1) if all peatlands currently drained globally
220 for cropland and grassland had the extent of drainage reduced by half (i.e., the water table is raised
221 halfway to the surface from its current depth). Approximately 60% of these emission reductions would
222 arise from temperate peatlands with an additional 25% in the tropics, illustrating the distribution of
223 current peatland agricultural use. Nitrous oxide emissions will also contribute to the GHG balance of
224 many paludiculture sites and were not included in the analysis by Evans et al. (2021). However, raising
225 the water level often reduces N₂O emissions as well (Karki et al. 2014, Hu et al. 2017), likely providing
226 additional GHG emission reductions.

227

228 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, vacuum-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)		

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

233 Other management practices with the potential to reduce peatland GHG emissions

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

239
240 In peat-rich regions where development occurs, infrastructure associated with industry or urban expansion
241 will result in peatland loss and can affect the function of the remaining peatlands adjacent to the
242 disturbance. For example, Saraswati & Strack (2019) determined that hydrologic changes that occur due
243 to peatland road-crossings result in measurable increases in CH₄ emissions from the adjacent peatland.
244 These impacts arise from a damming effect caused by the blockage of water flow by the road where
245 flooding on the upgradient side of the road results in enhanced CH₄ production and emissions that were
246 not compensated by the small emission reductions measured on the drier downgradient side. However,
247 this development-induced increase in CH₄ emissions was reduced by at least half when culverts were in
248 place to improve water flow and reduce impoundment (Saraswati & Strack 2019). Applying best
249 management practices during peat extraction, geologic exploration, forestry, and energy development
250 projects (e.g., oil well-pads and wind farms) could likely also lead to GHG emission reductions.
251 Unfortunately, we know little about the fate of peat carbon under these disturbances, the appropriate
252 management practices to apply, or the resulting GHG emissions reductions, making quantification of
253 these actions as potential NbS impossible at this time. As it is unlikely that all development of peatland
254 areas can be avoided, determining mechanisms to best protect peatland carbon stocks require further
255 study.

256
257 In addition to minimizing peatland disturbance, interest is also growing in management actions that could
258 enhance or protect carbon storage in relatively intact peatlands. While many peatland ecosystems will
259 likely continue to act as carbon sinks over the next century (Qiu et al. 2020), climate change will alter
260 disturbance regimes, enhancing permafrost thaw, fire frequency and severity, and periods of drought
261 and/or flooding, resulting in emission of stored peat carbon (Turetsky et al. 2015, Hugelius et al. 2020,
262 Loisel et al. 2020). While the best way to avoid the effects of these climate change-induced disturbances
263 is to limit warming through rapid reduction in GHG emissions, land management options have also been
264 discussed that could reduce carbon losses. For example, fuel management treatments have been tested in
265 boreal peatlands in an attempt to reduce wildfire severity, limiting release of peat carbon through
266 combustion (Wilkinson et al. 2018). Initial trials under a controlled burn observed a reduced depth of burn
267 under a canopy thinning treatment but shifts in peat bulk density and availability of fine fuels resulted in
268 greater carbon losses than control, untreated areas (Wilkinson et al. 2018); however, tests under a wider
269 range of conditions are needed. Given the extensive and growing area of peatland affected by wildfire
270 annual (Turetsky et al. 2015), the potential for emission reductions from fuel management could be large;
271 however, the feasibility of deployment and its ability to effectively reduce peat carbon losses has yet to be
272 clearly demonstrated and quantified.

273
274 Shifts in management of animal populations may also contribute to the protection of stored peat carbon.
275 Experiments are underway in Siberia to reintroduce large herbivores to reduce snowpack insulation and
276 retain permafrost (Beer et al. 2020). Early results indicate that grazing reduces CH₄ emissions but may

277 actually result in soil warming and drying that could accelerate soil C losses (Fischer et al. 2022). Longer
278 term studies are required to assess whether this management action will lead to GHG emission reductions.
279 Finally, beaver activity in and around peatlands can maintain high water levels (Karran et al. 2018) that
280 result in greater annual net ecosystem CO₂ uptake (He et al. 2021) and effectively rewet previously
281 drained peatlands (Minke et al. 2020). Thus, while beaver dams are often cleared by land managers to
282 alleviate flooding, maintenance of beaver populations and the resulting dams could be another NbS
283 strategy to enhance peatland carbon uptake and storage.

284 *Restoration and rewetting of peatland ecosystems*

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

297
298 At the ecosystem scale, GHG emission reductions associated with rewetting and restoration have been
299 demonstrated in a range of temperate and boreal peatland types and following a variety of disturbances
300 Application of the moss layer transfer technique in Canada resulted in the return of an annual net carbon
301 sink of $78 \pm 17 \text{ g C m}^{-2} \text{ yr}^{-1}$ to a bog following horticultural peat extraction by 15 years post-restoration
302 (Nugent et al. 2018). The return of CO₂ uptake post-restoration was also observed at restored cutover
303 peatlands in Ireland and Estonia, although accompanied by an increase in CH₄ emissions (Jarveoja et al.
304 2016; Renou-Wilson et al. 2019). Rewetting agricultural peatlands in California converted sites from
305 sources of up to $1250 \text{ g CO}_2 \text{ m}^{-2} \text{ yr}^{-1}$ and $15 \text{ g CH}_4 \text{ m}^{-2} \text{ yr}^{-1}$, to a CO₂ sink of up to $1455 \text{ g CO}_2 \text{ m}^{-2} \text{ yr}^{-1}$
306 with an increase in CH₄ emissions to $52\text{--}71 \text{ g CH}_4 \text{ m}^{-2} \text{ yr}^{-1}$ (Knox et al. 2015, Table 2). Similarly,
307 rewetting of agricultural peatlands in Germany led to GHG emission reductions that were enhanced by
308 removal of nutrient rich topsoil and introduction of *Sphagnum* moss (Huth et al. 2021). Although
309 concerns have been raised regarding the higher CH₄ emissions that occur due to shallow water table
310 following restoration, these are offset by substantial reductions in CO₂ emissions and the protection of the
311 remaining peatland carbon stock (Günther et al. 2020). Preventing ongoing mineralization of existing peat
312 carbon provides the greatest climate benefits leading to calls for rapid implementation of restoration
313 programs (Nugent et al. 2019; Günther et al. 2020).

314
315 In tropical peatland the soil water regime is one of the most important factors for controlling the carbon
316 balance (e.g., Hirano et al. 2014). It has been reported that soil heterotrophic respiration or peat
317 decomposition negatively correlated to ground water level (GWL). Their linear relationship indicates that
318 every 10 cm rise of GWL reduced CO₂ emission by $3.7 \text{ t CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$ in a burned degraded peatlands
319 (Hirano et al. 2014) and $7.3 \text{ t CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$ in a rubber plantation on drained peat (Wakhid et al. 2017) in

320 Central Kalimantan, Indonesia. As for ecosystem scale CO₂ balance, every 10 cm rise of minimum
321 monthly-mean GWL, which is usually measured in the late dry season, reduced net CO₂ emission by 1.8 t
322 CO₂ ha⁻¹ yr⁻¹ in peat swamp forests (Hirano et al. 2016). In contrast, as observed in northern peatlands,
323 CH₄ emissions both on the peat surface (Ishikura et al. 2019) and above peat forest (Wong et al. 2020)
324 increased exponentially with GWL until it rises to the ground level. For instance, 10 cm rise of GWL
325 from -30 cm increased ecosystem-scale CH₄ emission by 0.46 t CO₂e ha⁻¹ yr⁻¹ (Wong et al. 2020),
326 considering the global warming potential (GWP) of CH₄ of 34 over a timescale of 100 years (IPCC 2013).
327 Thus, the rewetting effect of reducing CO₂ emission would be offset to some extent by increasing CH₄
328 emission in the condition of relatively high GWL but still provides net GHG mitigation (Evans et al.
329 2021).

330
331 It is important to note that there is a transition period following restoration activities when GHG
332 emissions can be elevated or at least the peatland remains a source of carbon to the atmosphere as plants
333 become established (Nugent et al. 2019). Further, long term studies that monitor GHG emissions in
334 peatlands for over a decade remain rare (e.g., Wilson et al. 2016, Nugent et al. 2018) making the
335 definition of this transition period uncertain. Therefore, restoration actions must be seen as an investment
336 towards longer term climate change mitigation (e.g., Drever et al. 2021). Further, global estimates of the
337 potential for GHG emissions reductions for peatland restoration generally assume that all degraded
338 peatland areas are restored even though this may not be possible in practice suggesting these represent a
339 high end of potential emission reductions. With these considerations in mind, current global estimates for
340 GHG emission reductions related to peatland restoration range from 800 to 1900 Mt CO₂e in 2030 (Table
341 1).

342 Challenges and co-benefits associated with peatland NbS

343 The importance of protecting peatland carbon as part of climate change mitigation strategies is gaining
344 global attention (UNEP 2016), yet application of peatland NbS remains challenging. Managing peatlands
345 for carbon storage and GHG emission reductions requires tradeoffs with economic benefits and, in some
346 cases, other ecosystem services (Juutinen et al. 2021). Thus, willingness to implement peatland
347 management actions to reduce GHG emissions will depend on perceived balance between benefits and
348 costs, that will be stakeholder and context dependent (van Noordwijk et al. 2014, Buschmann et al. 2020).
349 The continued high level of uncertainty in estimates of actual GHG emission reductions from peatland
350 management actions adds to this challenge (e.g., van Noordwijk et al. 2014). Policy from local to global
351 levels is required to promote climate-friendly peatland management but may not achieve desired
352 outcomes. For example, in 2011 Indonesia implemented a moratorium on new forest concession licenses
353 for palm oil, timber and logging and reported GHG emission reductions of 11.2 Mt CO₂-e in 2017 due to
354 avoided deforestation and degradation (Groom et al. 2022). This action was partially supported by
355 economic incentives through the United Nations program Reducing Emissions from Deforestation and
356 Degradation (REDD+); Norway agreed to pay Indonesia USD \$56.2 million, based on a carbon price of
357 USD \$5 tCO₂-e⁻¹ (Groom et al. 2022). However, recent evaluation of the program indicates that, despite
358 the moratorium, no reduction in peatland forest loss was detected compared to projected rates, suggesting
359 that the program was ineffective in avoid disturbance and reducing GHG emissions (Groom et al. 2022).
360 This indicates that effective peatland management for GHG emission reduction requires interdisciplinary
361 and multi-stakeholder collaboration that promotes iterative evaluation of policy and actions as new

362 information becomes available. The involvement of local communities adds to the challenge of
363 collaboration across an often-diverse group of stakeholders but is critical for peatland management
364 (Mishra et al. 2021). Although the global motivation for peatland restoration is to reduce carbon emission,
365 local stakeholders require direct benefit from peatlands. Since many people are living in and around
366 peatlands, particularly in temperate and tropical regions, it is indispensable for local people to participate
367 in the activities at all stages.

368
369 Moreover, ongoing climate change will pose challenges due to altered water resource availability, the
370 occurrence of extreme events, and shifting land-use pressures that may create competing priorities for
371 land and resources needed for peatland NbS pathways. For example, water availability is necessary for
372 peatland rewetting projects. Although this may not be an issue for many peatlands, changing precipitation
373 patterns, local hydrologic conditions and/or sea level rise may limit the availability of water of suitable
374 quality at the appropriate times of year for rewetting activities (Acreman et al. 2007). Demands for future
375 food production will likely also place limits on the extent of peatland restoration and/or shifts to
376 paludiculture (Tan et al. 2021). Further, studies suggest demand for horticultural peat will continue to
377 expand to meet rising greenhouse-based food production providing additional pressure for peat extraction
378 if alternative growing media cannot meet the demand (Blok et al. 2019). Northward expansion of resource
379 extraction will continue to put pressure on boreal and subarctic peatlands, requiring policy mechanisms
380 that support long term peatland conservation to avoid conversion and the associated GHG emissions
381 (Harris et al. 2021). Even when protected from development, climate change-induced disturbance also
382 places peatland C stocks at risk and this needs to be accounted for when including peatland NbS in
383 climate change mitigation strategies (Coffield et al. 2021).

384
385 Despite the challenges involved with using peatlands as a NbS, the avoided conversion, better
386 management and restoration of peatlands provides a vast array of co-benefits. These include flood
387 management and maintenance of water quality (Ritson et al. 2016), reduced land subsidence (Knox et al.
388 2015), fire risk management (Granath et al. 2016) and human well-being (IUCN, 2018). For example,
389 when in good condition, peatlands can not only provide mitigation to regional climate warming (Helbig et
390 al. 2020), acting as cool humid islands on the landscape due to the wet conditions found there (Worrall et
391 al. 2020) but also have greater resilience to a number of climatic changes including wildfire (Kettridge et
392 al. 2017, Taufik et al. 2022). A reduction in peat fires will also have direct positive human health and
393 economic benefits through by reducing property loss and the frequency and severity of haze events (Hu et
394 al. 2018). Peatlands globally provide habitat for rare and endangered species such as the woodland
395 caribou (*Rangifer tarandus caribou*) (Barber et al. 2018) and the orangutan (*Pongo pygmaeus*) (Felton et
396 al. 2003). Furthermore, the rewetting and restoration of peatlands can re-establish ecological diverse plant
397 communities (Renou-Wilson et al. 2019). The restoration of degraded peatland habitats can not only
398 prevent further decline of endangered species but could also enhance overall biodiversity. Finally,
399 maintenance of intact peatlands also protects the land-base for many Indigenous communities globally,
400 who use peatland landscapes in a variety of ways, including for subsistence hunting and food foraging
401 (David Suzuki Foundation, 2013).

402 Conclusions

403 Globally, peatland ecosystems represent the largest terrestrial organic C stock with at least 600 Gt of
404 stored carbon. Preventing its release to the atmosphere can play an important role in slowing
405 anthropogenic climate change. A combination of avoiding future peatland conversion and mitigation or
406 halting release of carbon from currently disturbed peatlands through rewetting and restoration has the
407 potential to contribute a reduction in GHG emissions of 1.1 to 2.6 Gt CO₂e yr⁻¹ in 2030 (Table 1). In order
408 to achieve these emission reductions, policies from local to international levels are needed to protect
409 carbon sink function in the majority of currently undeveloped, intact peatlands and support rewetting of
410 those currently drained (Moomaw et al. 2018). Effective implementation will require collaboration across
411 levels of government, with industrial and agricultural land-users, and with local communities and
412 Indigenous peoples that depend on peatlands for livelihoods and traditional use. Ongoing climate
413 warming continues to pose additional threats to peatland carbon stocks due to increased decomposition
414 under warmer temperatures and drought, wildfires, and permafrost thaw. Therefore, gaining benefits from
415 peatlands as NbS also requires rapid reduction in fossil fuel GHG emissions to limit warming and provide
416 the best chance to maintain these ecosystems within suitable conditions for maintenance of net carbon
417 sink function into the future.

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422

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427 Conflict of Interest Statement

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

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