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Wildfire and degradation accelerate northern peatland carbon release

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Abstract:

The northern peatland carbon sink plays a vital role in climate regulation; however, the future of this carbon sink is uncertain, in part, due to the changing interactions of peatlands and wildfire. Here, we provide the first estimates of carbon emissions associated with boreal and temperate non-permafrost peatlands that specifically include peatland degradation status, wildfire combustion and post-fire dynamics. Wildfire processes reduced the magnitude of carbon uptake in pristine peatlands by 35 % and further enhanced emissions from degraded peatlands by 10 %. The system's current small net sink is vulnerable to the interactions of peatland degraded area, burn rate, and peat burn severity. Modelled climate change impacts accelerated carbon losses and weakened the carbon sink function (burn severity; 38 % reduction and burn rate; 65 % reduction, by 2100), however, we also demonstrate the potential for active peatland restoration to buffer these impacts.

1 Peatlands store approximately one-third of the global soil carbon stock in 3 % of the land
2 area, making them the most carbon dense ecosystem on Earth¹. Northern peatlands, in
3 boreal and temperate regions, account for ~90 % of global peatland area² and have
4 sequestered ~500 Gt C since the last glacial maximum^{1,3}, regulating the global climate
5 throughout the Holocene⁴. Yet, the future of this peatland carbon stock is uncertain⁵⁻⁷, in
6 part, due to the changing interactions of peatlands and wildfire⁸⁻¹⁰. Despite the critical role
7 of peatlands in the global carbon cycle, recent reports and literature that may influence
8 policy do not explicitly account for the impacts of fire on peatland emissions estimates
9 (e.g.,¹¹). While estimates of the contribution of peatland drainage to global GHG
10 emissions have been made^{12,13}, no such evaluation has been conducted for, or includes,
11 the interacting effects of peatland degradation and wildfire. The absence of this
12 assessment results in additional uncertainty regarding the impact of climate change on
13 the peatland carbon sink¹².

14
15 Carbon emissions from pristine peatland wildfires can vary considerably, however, they
16 typically average 1–5 kg C m⁻² ^{10,14,15}. These relatively small peat carbon losses from
17 combustion can be re-accumulated within 10 to 30 years post-fire¹⁶, enabling peatlands
18 to remain a net carbon sink over typical fire-free intervals^{17,18}. Conversely, peatland
19 degradation, such as peatland drainage, not only increases ignition potential¹⁹ but can
20 also inflate carbon emissions from peatland wildfires by one or more orders of magnitude,
21 to 10–25 kg C m⁻² equating to 500 to >1000 years of carbon sequestration^{10,15,19,20}. Given
22 that >25 Mha (7 %) of boreal and temperate peatlands have been drained for
23 anthropogenic use²¹, with some regional or national estimates of ~50 %¹¹, these
24 degraded peatlands represent high risk areas where wildfire could lead to large carbon
25 emissions.

26
27 The difference in net carbon fluxes between pristine and drained peatland wildfires are
28 exacerbated when examining post-fire dynamics. Alterations to CO₂ and methane (CH₄)
29 fluxes immediately after fire affect the short-term carbon balance²²⁻²⁴ while post-fire
30 vegetation recovery controls the long-term carbon balance^{8,16}. While most pristine
31 peatlands return to a net carbon sink post-fire, evidence suggests that the greater burn
32 severity in degraded peatlands increases the potential for ecosystem regime shifts⁸, a
33 change from a carbon accumulating peatland to a carbon releasing ecosystem with non-
34 peatland vegetation, further increasing the impact of peatland wildfires on long-term
35 carbon balance. As such, the inclusion of peatland drainage and post-fire net carbon
36 fluxes is paramount for the accurate evaluation of peatland wildfire carbon emissions.

37
38 Rapid changes to regional wildfire regimes are compounding the impacts of drainage on
39 peatland wildfire. In the boreal zone, annual area burned²⁵ and the frequency of extreme
40 fire weather conditions²⁶ are increasing as enhanced evapotranspiration is leading to drier

41 wildfire fuels, particularly in peatland ecosystems²⁷. Similarly, in the temperate zone
42 increased wildfire activity has been associated with severe droughts²⁸, and long-term
43 drying has been observed in peatlands²⁹. Increased lightning occurrence, reduced
44 snowpacks and multi-year droughts are predicted to further increase annual area
45 burned³⁰. Such combinations of climate change-mediated stressors in northern
46 peatlands, along with pervasive peatland degradation, are likely to increase peatland burn
47 rate (percent of peatland area burned per year), peat burn severity, and associated
48 carbon losses^{9,10}. Despite evidence that individual northern peat fires can produce
49 teragrams of carbon emissions^{20,31}, the fire return interval (FRI) in northern peatlands is
50 often only assessed on a regional or per-site basis (e.g.,³²). The lack of consistent
51 methodology for assessing peatland burn rate across northern regions has hindered the
52 evaluation of the current and future contribution of northern peatland fires to global carbon
53 emissions. Hence, here we provide the first estimates of spatially explicit northern
54 peatland burn rates and the contribution of peatland wildfire and post-fire dynamics to
55 global carbon emissions. We then illustrate the impact of peatland degradation and
56 climate change on the future of the northern peatland carbon sink.

57

58 **Empirical modelling of peatland net ecosystem exchange and methane emissions**

59 To address this challenge, we undertook a synthesis of empirical datasets from natural,
60 degraded (currently drained or previously drained and unrestored), and restored
61 peatlands in non-permafrost boreal and temperate regions. We then used these data to
62 model the net ecosystem exchange (NEE; CO₂) and CH₄ fluxes of peatlands over time,
63 integrating post-fire dynamics (recovery rate and final NEE) and averaging over a
64 distribution of FRIs (Table ED1, Methods). The inclusion of peat carbon loss from
65 combustion and post-fire net carbon fluxes reduced the mean (sd) NEE and CH₄ flux sink
66 strength from -50.7 (61.8) g C m⁻² yr⁻¹ (No Burn - natural) to -32.9 (63.2) g C m⁻² yr⁻¹ in
67 natural (pristine) peatlands experiencing fire. The moderate (~35 %) reduction in the sink
68 strength evidences the impact of fire on peatland carbon balance but also the resilience
69 of the natural peatland carbon sink function under a typical wildfire regime (Fig. 1).

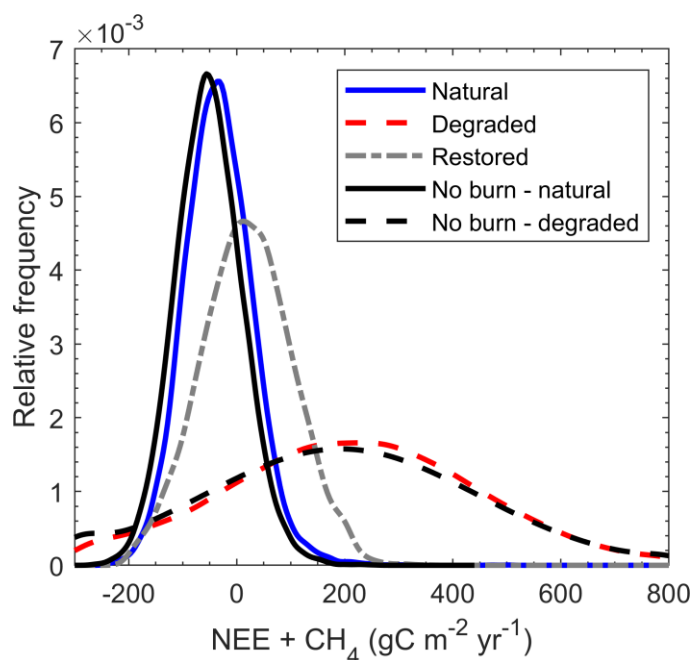
70

71 Across the variability in burn rate and the impacts of the fire (i.e., severity, recovery rate)
72 the NEE + CH₄ of degraded peatlands remained a consistent source of carbon with an
73 average flux of 213 (229) g C m⁻² yr⁻¹ to the atmosphere, a 10 % increase compared to
74 No burn – degraded (194 (242) g C m⁻² yr⁻¹). Meanwhile, the restoration of peatlands prior
75 to fire mitigated extensive carbon release (92 % reduction in emissions compared to
76 Degraded), yet restored peatlands remained a small source of carbon with average NEE
77 + CH₄ emission of 17.3 (85.5) g C m⁻² yr⁻¹ (Fig. 1). As such, our modelling indicates that
78 excluding peatland wildfire from peatland NEE and CH₄ calculations results in a
79 misrepresentation of peatland carbon balance and may impact estimated regional to

80 national emissions budgets, especially in fire-prone areas with a high proportion of
81 degraded peatlands.

82
83 Our empirical approach includes uncertainty in the magnitude of peat carbon loss, burn
84 rate, the rate of recovery, and the initial and final recovered NEE (Methods, Figure ED1).
85 Our synthesis highlighted limited availability of post-fire carbon flux data, especially from
86 degraded and restored sites, resulting in a wider distribution of modelled NEE and CH₄
87 flux in these scenarios. To further constrain peatland NEE and CH₄ distributions and
88 accurately include peatlands in earth system models, plot- to ecosystem-scale carbon
89 flux data at varying times post-fire, especially in degraded and restored ecosystems, is a
90 critical research need.

91



92
93 Fig. 1. Distribution of net ecosystem exchange (NEE) and methane (CH₄) fluxes derived from
94 Monte Carlo simulation model outputs accounting for variation in the magnitude of peat carbon
95 loss from combustion, burn rate, the rate of recovery, and the initial and final recovered NEE for
96 peatlands. The same burn rate distribution is used for all peatland states across simulations
97 (Methods). Categories of peatland states include Natural (pristine), Degraded, and Restored (prior
98 to fire), and not accounting for wildfire; No burn – natural and No burn - degraded.

99

100 **Effect of climate-mediated drying and changes to burn rate on peat fire emissions**

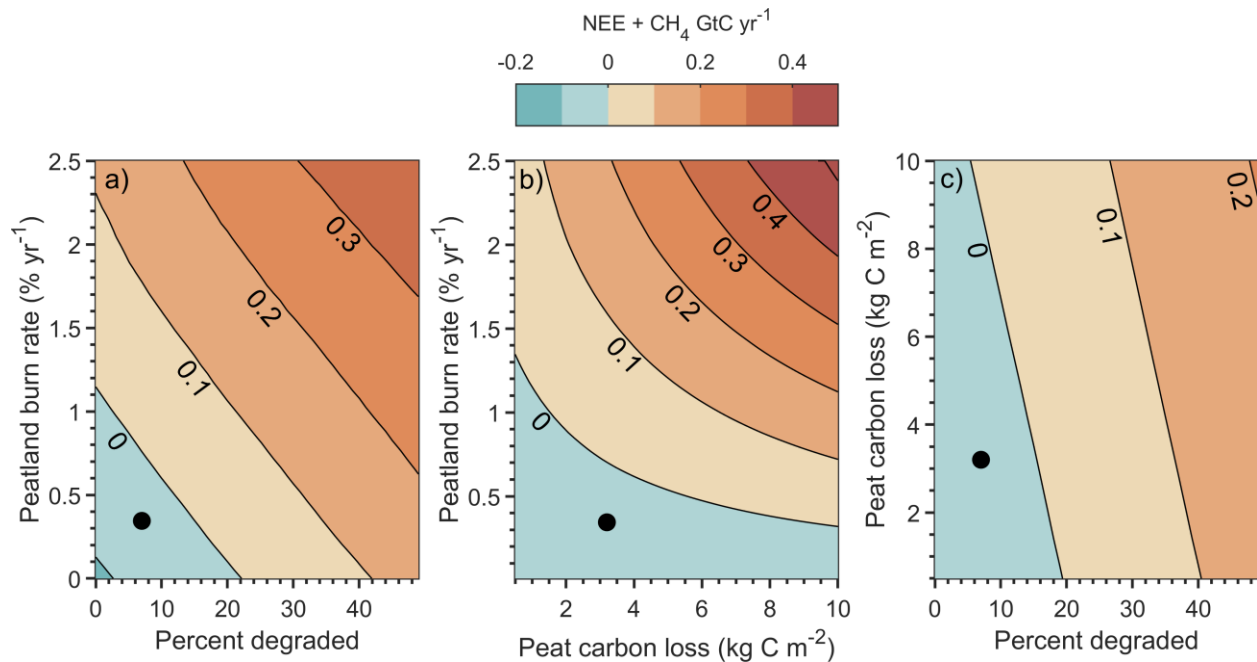
101 In addition to the impact of degradation, peatland NEE + CH₄ fluxes are also sensitive to
102 the increasing pressures of climate-mediated drying and associated increases in peat
103 carbon loss from combustion¹⁰. By aggregating a global dataset of fire perimeters from
104 2001–2021 (FIRE⁴⁴; Fig. S1), we calculated the average burn rate (percent of land area
105 burned per year) for boreal and temperate non-permafrost regions over the last two
106 decades (Methods). Average burn rate varied between 0.0001 and 1.48 % yr⁻¹ amongst

107 boreal and temperate ecoregions (Table S1), with a spatially weighted average of 0.35 %
108 yr⁻¹, equivalent to a FRI of 290 years. Assessment of the relationship between peatland
109 (histosol) areal coverage³ and burn rate found no significant trends (Fig. ED2, S2 and
110 S3), suggesting that peatland cover does not exert a strong control over regional area
111 burned. Compilation of national inventories found that degradation due to drainage for
112 agriculture, horticulture, and forestry varies between <1 and 54 % of peatland area per
113 country³⁴ and the proportion of total drained northern peatland area is ~7 % (26.1 Mha;
114 ²¹). These data were used to evaluate the current state of the boreal and temperate non-
115 permafrost peatland system.

116
117 At the broadest scale, without accounting for future climate change impacts to peatlands
118 or wildfire regimes, we estimate that the total NEE + CH₄ flux for boreal and temperate
119 non-permafrost peatlands is a small net carbon sink (filled dots Fig. 2), however, the
120 system becomes a net carbon source given an annual average peatland burn rate of
121 more than 0.77 % based on the current estimates of drained peatland area (Fig. 2a).
122 Accordingly, and important for regional carbon balances, a greater percentage of
123 degraded peatlands reduces the burn rate required to switch the system from a net carbon
124 sink to a net carbon source by 0.05 % yr⁻¹ per additional 1 % degraded peatland area.

125
126 Similarly, increased peat carbon loss from combustion reduces the carbon sink strength
127 and may contribute to switching the system to a net source. Increasing the average peat
128 carbon loss from combustion in pristine peatlands to represent a moderate degree of
129 climate change drying (1.5 kg C m⁻² added to the original distribution; Methods) reduces
130 the annual burn rate required to switch from a carbon sink to source to 0.55 % (Fig. 2b).
131 This equates to a required lengthening of the average FRI by ~50 years to maintain active
132 net carbon sequestration at a landscape level. Further, there is a strong interactive effect
133 of percent degraded and peat carbon loss on NEE + CH₄ (Fig. 2c). Using the spatially
134 weighted average burn rate of 0.35 % yr⁻¹, NEE + CH₄ fluxes are sensitive to changes in
135 percent degraded, where a relatively small reduction in percent degraded (e.g., by one-
136 third from 15 to 10 %) via active restoration counteracts potential increases in average
137 peat carbon loss from combustion caused by climate-mediated drying.

138



139
140

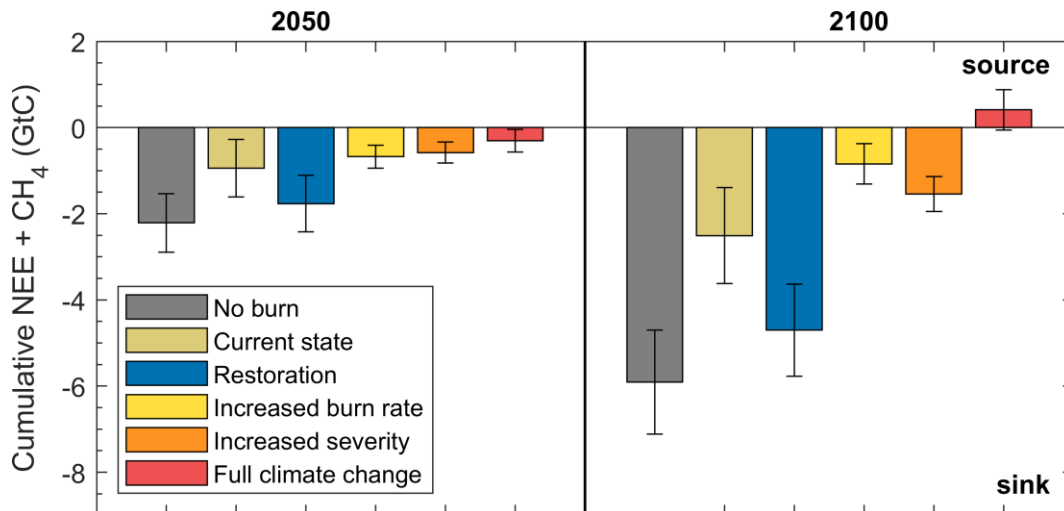
141 Fig. 2. The interactive effect of fire regime changes and degraded peatland area, on NEE + CH₄
 142 (GtC yr⁻¹). a) Peatland burn rate and percent degraded, where peat carbon loss is weighted based
 143 on percent degraded. b) Peatland burn rate and peat carbon loss, where percent degraded is
 144 held constant at 7 %. c) Peat carbon loss and percent degraded, with a 0.35 % (spatially-weighted
 145 average) burn rate. Filled dots represent the current boreal and temperate non-permafrost
 146 peatland system in the NEE and CH₄ flux phase space. Axes do not show zero where a zero
 147 value results in a no-data point.

148

149 The future of the northern peatland carbon sink

150 To illustrate the impact of peatland degradation status and climate change on the
 151 magnitude of the peatland carbon sink we evaluated cumulative annual net fluxes from
 152 our NEE + CH₄ simulations. We developed scenarios that combine different peatland
 153 degradation and climate change factors and assessed the impact on total carbon
 154 sequestration (or emission) by 2050 and 2100 (Methods). Scenarios include i) No burn,
 155 ii) Current state, iii) Restoration, iv) Increased burn rate, v) Increased (burn) severity, and
 156 vi) Full climate change (increased burn rate and burn severity).

157



158
159

160 Fig. 3. Cumulative NEE + CH₄ flux (GtC) for boreal and temperate non-permafrost peatlands in
161 2050 and 2100. Negative values represent a carbon sink while positive values represent a carbon
162 source. Scenarios include: Current state, No burn (Current state with 0 % burn rate), Restoration
163 (100 % of degraded peatlands restored), Increased burn rate (annual rate doubling by 2100),
164 Increased severity (additional 1.5 kg C m⁻² loss across all peatland states), and Full climate
165 change (increased burn rate and severity). Error bars (±1 sd) represent the uncertainty estimated
166 via Monte Carlo simulations using distributions of burn rate and NEE + CH₄.

167

168 Accounting for peatland wildfire emissions reduces the magnitude of the estimated
169 peatland carbon sink by 1.3 GtC, or 57 %, by 2050 when comparing the No burn scenario
170 (-2.2 GtC) to our Current scenario (-0.94 GtC; Fig. 3). Meanwhile, the restoration of all
171 degraded peatlands (Restoration scenario) results in a sink of 1.8 GtC by 2050, an
172 additional 0.82 GtC sequestered compared to the Current scenario, evidencing the short-
173 term gains to be made from peatland restoration. Restoration increases the carbon sink
174 by almost 90 % in 2100, increasing it from a sink of 2.5 (Current scenario) to 4.7 GtC
175 (Restoration scenario).

176

177 Increasing peatland burn rate (linear increase to 0.7 % by 2100) and increasing burn
178 severity (+1.5 kg C m⁻² peat carbon loss) decrease the peatland carbon sink by similar
179 amounts by 2050 with a 0.25 and 0.36 GtC reduction relative to the Current scenario,
180 respectively. However, the modelled burn rate increase throughout the remainder of the
181 century results in a large decrease in the carbon sink strength in the Increased burn rate
182 scenario by 2100, reducing the total carbon sequestration to a sink of 0.88 GtC, a 65 %
183 decrease compared to the Current scenario (-2.5 GtC). Concerningly, when the impacts
184 of climate change are combined (Full climate change scenario) the system shows a
185 potential switch from a carbon sink to a carbon source, with a mean estimated source of
186 0.4 GtC to the atmosphere by 2100. The acceleration of carbon release from boreal and
187 temperate non-permafrost peatlands and associated diminishment of the strength of the

188 carbon sink over the coming decades has critical implications for global climate change
189 and emissions targets.

190 **Assessing the importance of peatland restoration for global climate change and**
191 **emissions targets**

192 This study highlights the resilience of pristine northern peatland ecosystems to wildfire,
193 with natural peatlands returning to a net carbon sink in most of our simulations across the
194 range of fire severity and post-fire dynamics. Conversely, we demonstrate unequivocally
195 that degraded peatlands are responsible for the largest peatland carbon emissions^{19,20,31}.
196 We show that the restoration of degraded peatlands prior to fire greatly reduces long-term
197 emissions³³. Our results add to the growing literature base that suggests climate and land-
198 use change increase the vulnerability of peatland ecosystems and their carbon stocks to
199 fire, with significant and far-reaching ecological, hydrological, and societal
200 consequences^{34,35}.

201
202 While future anthropogenic fossil fuel emissions can be curbed, the climatic changes
203 already induced by rising atmospheric CO₂ concentrations will likely continue to increase
204 peatland wildfire emissions over the coming century, reducing the strength of the peatland
205 carbon sink. We show that although the peatland carbon sink is currently resilient,
206 changes in degraded peatland area, average burn rate (FRI) and peat burn severity may
207 lead to climate neutrality or net carbon release. Climate-mediated peatland drying across
208 the spectrum of peatland condition^{27,29} could contribute to increases in peatland burn
209 rate³⁶ and peat carbon loss via enhanced burn severity¹⁰ in line with the increasing
210 availability of critically dry peatland fuels⁹. Forested peatlands (natural or managed) may
211 be more prone to positive (amplifying) ecohydrological feedbacks that promote high
212 severity smouldering fire³⁷, when compared to arable peatlands in northern regions,
213 however, the vulnerability of peatlands to wildfire under different management regimes is
214 currently relatively unstudied.

215
216 To maintain the northern peatland carbon sink function, decreases in the area of
217 degraded peatland through active peatland restoration must occur to counteract potential
218 increases in average peat carbon loss due to climate-mediated drying. Our restoration
219 scenario (representing the restoration of all degraded peatlands) resulted in an estimated
220 increase in the carbon sink by almost 90 % by 2100 compared to the current scenario.
221 Despite the hypothetical nature of our restoration scenario, it serves to support research
222 highlighting the important role peatlands can play in reducing global emissions if they are
223 protected³⁸ and restored³⁹ appropriately. We also strongly advocate for better
224 management of carbon-rich ecosystems alongside behavioural changes to stop
225 accidental and unnecessary ignitions⁴⁰ especially areas with a high proportion of
226 degraded peatlands (e.g., Europe)¹¹.

227
228 On a regional level we provide evidence of the importance of accurately measuring
229 (degraded) peatland area, as well as burn rate, since these factors will affect the ability
230 of countries/regions to account for emissions and potentially, to achieve emissions
231 targets. The proportion of peatlands affected by land use change varies considerably
232 between countries and regions but can be substantial (<1 to ~50 % degraded⁴¹). While
233 there are likely differences in the ignition potential of different peatland land-uses¹⁹ there
234 is a scarcity of these data in the literature. Peatland type and landscape position have
235 been found to impact burn rate³² and fire severity⁴², yet peatlands are often misclassified
236 in fire risk, spread, and emissions models⁴³, highlighting the need to improve peatland
237 mapping for use alongside remotely sensed fire products (e.g.,⁴⁴). Appropriate accounting
238 of carbon emissions from peatlands, accounting for wildfire, may guide national/regional
239 restoration and conservation strategies (e.g., the UK⁴⁵).

240
241 Interdisciplinary collaborations will be crucial to accurately represent the northern
242 peatland carbon balance in earth system models and ensure community- to international-
243 level climate policies include important peatland processes, such as fire, in their strategies
244 to maintain the impacts of climate change within liveable bounds. While remote-sensing
245 applications, such as FIRED⁴⁴, have enabled consistent burn rate mapping across large
246 regions, the limited precision and consistency of peatland type and carbon stock maps
247 creates challenges for further reducing the uncertainty surrounding estimates of the
248 strength of the northern peatland carbon sink³⁸. Further, our carbon sink estimates don't
249 account for fluvial export of carbon, nor the anthropogenic additions/removals of biomass
250 on agricultural peatlands. Data corresponding to methane emissions in different peatland
251 types immediately post-fire e.g.,^{22,23} would further constrain estimates of the peatland
252 carbon sink.

253
254 The direction and magnitude of the peatland-climate feedback will be driven by the
255 combined effects of peatland degradation and restoration, and the global emissions
256 pathway that will influence rates of climate-induced drying²⁷ and changes in burn rate²⁶.
257 Northern peatlands have regulated global climate over the Holocene but if the predicted
258 increases in peat burn severity and fire activity outweigh carbon sequestration from
259 peatland expansion in high-latitude regions⁴⁷, the northern peatland system will become
260 a shrinking carbon sink and a potential future carbon source, exacerbating the rapidly
261 closing window of time to avoid the most severe impacts of global climate change. Our
262 scenario results found that increasing burn rate and peat burn severity drastically reduced
263 the amount of carbon sequestered in peatlands, but overall the system maintained a
264 carbon sink status in 2050. However, the continued and compounding impacts of climate
265 change resulted in an estimated small net carbon source to the atmosphere by boreal
266 and temperate non-permafrost peatlands by 2100. Notably this estimate does not account

267 for increased peatland tree growth stimulated by drier conditions¹⁰, however, given the
268 positive correlation between tree size and burn severity¹⁰ and the dominance of long-term
269 carbon storage in peat rather than above-ground vegetation⁴⁸, it is unlikely that increases
270 in above-ground biomass will translate into significant increases in carbon storage over
271 long (>1 FRI) time periods. The likely reduction in peatland carbon sink strength will create
272 further challenges to remaining below critical global climate targets.

273

274 Against the global backdrop of increases in burn rate and extreme wildfire weather²⁶,
275 integrated regional wildfire management solutions are urgently required to mitigate severe
276 climatic and societal impacts of peatland wildfire^{36,37}. In regions with higher proportions
277 of peatland degradation we find that a strong trade-off with burn rate (i.e., large
278 investments in direct fire suppression) is required to preserve the critical climate
279 regulation function of peatlands. Where this balance is not maintained peatland wildfire
280 emissions may represent an under-appreciated source component in carbon accounting
281 that could be detrimental to achieving emissions targets. We demonstrate here that,
282 despite notable impacts of peatland burn rate and burn severity, peatland restoration
283 represents a large opportunity to minimize impacts to the boreal and temperate peatland
284 carbon sink over the coming century when accounting for peatland wildfire emissions.
285 Our results suggest an immediate need to start including active restoration of degraded
286 peatlands as a cost-effective tool to support the mitigation of extensive carbon emissions
287 and detrimental impacts on human health.

288

289

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298

299 **Competing Interests**

300 The authors have no relevant financial or non-financial interests to disclose.

301

302 **Author Contributions**

303 SW: Conceptualisation, data curation, formal analysis, methodology, visualization, writing
304 – original draft, writing – review & editing. RA: Conceptualisation, methodology,
305 visualization, writing – review & editing. PM: Data curation, formal analysis, methodology,
306 writing – review & editing. SD: Data curation, writing – original draft, writing – review &
307 editing. GG: Data curation, writing – original draft, writing – review & editing. JMW:
308 Conceptualization, funding acquisition, methodology, supervision, writing – review &
309 editing.

310

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472
 473 **Extended Data**

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 475 Table ED1. Input parameters derived from data synthesis used in Monte Carlo simulations for
 476 calculation of peatland net ecosystem carbon balance. The restored group here includes
 477 rewetted sites. The fire return interval used in the model is taken from the burn rate as 100/(burn
 478 rate).

Input	State	Distribution	Parameter 1	Parameter 2
NEE (g C m ⁻² yr ⁻¹)	burned	Normal	Mean = 71.4	SE = 53.6
	degraded	Normal	Mean = 191.8	SE = 249.5
	restored	Normal	Mean = -5.7	SE = 84.7
	pristine	Normal	Mean = -62.6	SD = 57.8
Fire C-loss (kg C)	degraded	log-normal	Mean = 1.846	SD = 0.846
	pristine	log-normal	Mean = 0.587	SD = 0.907
Burn rate (% yr ⁻¹)	–	exponential	Mean = 0.345	N/A
t_1	–	uniform	Min. = 1	Max. = 10
t_2	–	uniform	Min. = 11	Max = 60

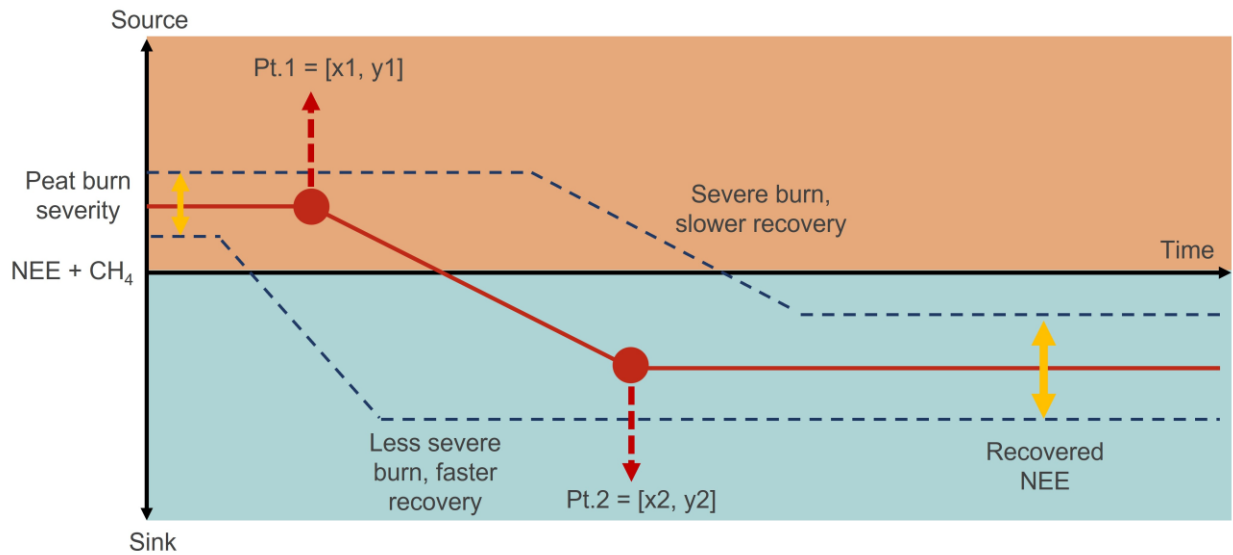
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 482 Table ED2. Data from FIRED (non-permafrost land area) with area burned over a 19.75 year
 483 period from 2001 to 2021. Only ecoregions within each biome which contained peatlands
 484 (histosols) were considered.

Region	Biome	Total area (10⁶ km²)	Burned area (10⁶ km²)	Fire return interval (years)	Burn rate (% yr⁻¹)
Asia	Boreal	3.08	0.261	233	0.43
	Temperate	3.93	0.452	172	0.58
Europe	Boreal	2.32	0.022	2,060	0.05
	Temperate	4.55	0.320	281	0.36
North America	Boreal	3.37	0.238	279	0.36
	Temperate	3.08	0.089	682	0.15

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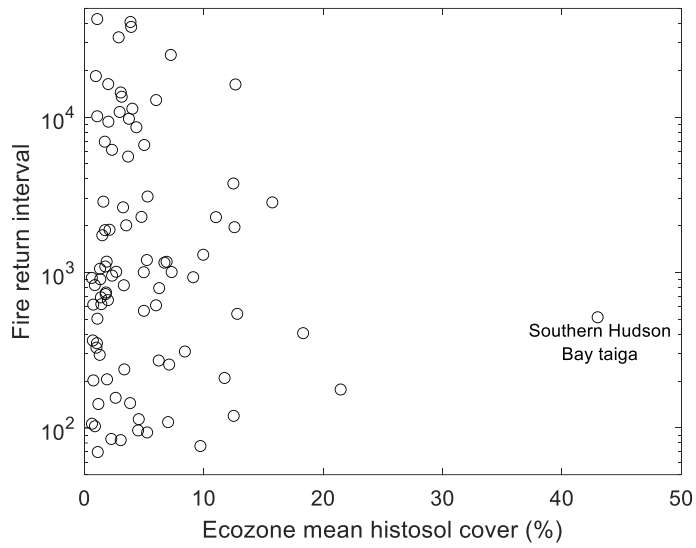
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Figure ED1. Conceptual diagram of the modelling design developed to incorporate peat carbon loss from wildfire (peat burn severity) and post-fire carbon dynamics (recovery rate and recovered net ecosystem exchange (NEE)) in peatland GHG emissions. Where y_1 represents the NEE + CH₄ of a burned peatland, x_1 represents the time lag between wildfire and the initiation of post-fire recovery, x_2 represents the time at which “recovered” NEE is achieved and y_2 represents the magnitude of the recovered carbon sink. The variability in peat burn severity, time lag, recovery rate, and recovered NEE are depicted by the blue dashed lines and yellow arrows.

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503 Figure ED2. Fire return interval ($100/(\text{burn rate})$) per ecozone, and mean ecozone histosol

504 cover. The Southern Hudson Bay taiga ecozone is highlighted as the region with the highest

505 histosol cover (~43%).