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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.

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

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

The difference in net carbon fluxes between pristine and drained peatland wildfires are exacerbated when examining post-fire dynamics. Alterations to CO_2 and methane (CH_4) fluxes immediately after fire affect the short-term carbon balance[22-24] while post-fire vegetation recovery controls the long-term carbon balance[8,16]. While most pristine peatlands return to a net carbon sink post-fire, evidence suggests that the greater burn severity in degraded peatlands increases the potential for ecosystem regime shifts[8], a change from a carbon accumulating peatland to a carbon releasing ecosystem with non-peatland vegetation, further increasing the impact of peatland wildfires on long-term carbon balance. As such, the inclusion of peatland drainage and post-fire net carbon fluxes is paramount for the accurate evaluation of peatland wildfire carbon emissions.

Rapid changes to regional wildfire regimes are compounding the impacts of drainage on peatland wildfire. In the boreal zone, annual area burned[25] and the frequency of extreme fire weather conditions[26] are increasing as enhanced evapotranspiration is leading to drier wildfire fuels, particularly in peatland ecosystems[27]. Similarly, in the temperate zone increased wildfire activity has been associated with severe droughts[28], and long-term drying has been observed in peatlands[29]. Increased lightning occurrence, reduced snowpacks and multi-year droughts are predicted to further increase annual area burned[30]. Such combinations of climate change-mediated stressors in northern peatlands, along with pervasive peatland degradation, are likely to increase peatland burn rate (percent of peatland area burned per year), peat burn severity, and associated carbon losses[9,10]. Despite evidence that individual northern peat fires can produce teragrams of carbon emissions[20,31], the fire return interval (FRI) in northern peatlands is often only assessed on a regional or per-site basis (e.g.,[32]). The lack of consistent methodology for assessing peatland burn rate across northern regions has hindered the evaluation of the current and future contribution of northern peatland fires to global carbon emissions. Hence, here we provide the first estimates of spatially explicit northern peatland burn rates and the contribution of peatland wildfire and post-fire dynamics to global carbon emissions. We then illustrate the impact of peatland degradation and climate change on the future of the northern peatland carbon sink.

Empirical modelling of peatland net ecosystem exchange and methane emissions

To address this challenge, we undertook a synthesis of empirical datasets from natural, degraded (currently drained or previously drained and unrestored), and restored peatlands in non-permafrost boreal and temperate regions. We then used these data to model the net ecosystem exchange (NEE; CO_2) and CH_4 fluxes of peatlands over time, integrating post-fire dynamics (recovery rate and final NEE) and averaging over a distribution of FRIs (Table ED1, Methods). The inclusion of peat carbon loss from combustion and post-fire net carbon fluxes reduced the mean (sd) NEE and CH_4 flux sink 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 natural (pristine) peatlands experiencing fire. The moderate (~35 %) reduction in the sink strength evidences the impact of fire on peatland carbon balance but also the resilience of the natural peatland carbon sink function under a typical wildfire regime (Fig. 1).

Across the variability in burn rate and the impacts of the fire (i.e., severity, recovery rate) the NEE + CH_4 of degraded peatlands remained a consistent source of carbon with an average flux of 213 (229) g C m^{-2} yr^{-1} to the atmosphere, a 10 % increase compared to No burn – degraded (194 (242) g C m^{-2} yr^{-1}). Meanwhile, the restoration of peatlands prior to fire mitigated extensive carbon release (92 % reduction in emissions compared to Degraded), yet restored peatlands remained a small source of carbon with average NEE + CH_4 emission of 17.3 (85.5) g C m^{-2} yr^{-1} (Fig. 1). As such, our modelling indicates that excluding peatland wildfire from peatland NEE and CH_4 calculations results in a misrepresentation of peatland carbon balance and may impact estimated regional to national emissions budgets, especially in fire-prone areas with a high proportion of degraded peatlands.

Our empirical approach includes uncertainty in the magnitude of peat carbon loss, burn rate, the rate of recovery, and the initial and final recovered NEE (Methods, Figure ED1). Our synthesis highlighted limited availability of post-fire carbon flux data, especially from degraded and restored sites, resulting in a wider distribution of modelled NEE and CH_4 flux in these scenarios. To further constrain peatland NEE and CH_4 distributions and accurately include peatlands in earth system models, plot- to ecosystem-scale carbon flux data at varying times post-fire, especially in degraded and restored ecosystems, is a critical research need.

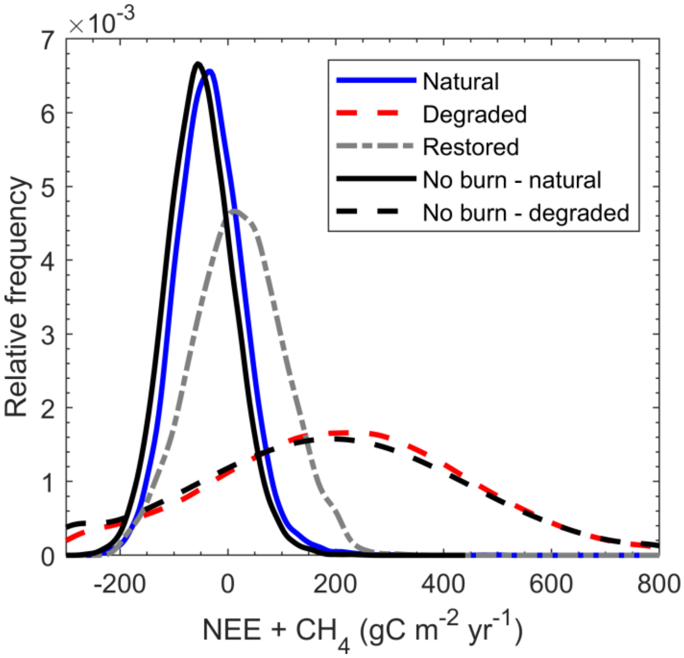

Fig. 1. Distribution of net ecosystem exchange (NEE) and methane (CH_4) fluxes derived from Monte Carlo simulation model outputs accounting for variation in the magnitude of peat carbon loss from combustion, burn rate, the rate of recovery, and the initial and final recovered NEE for peatlands. The same burn rate distribution is used for all peatland states across simulations (Methods). Categories of peatland states include Natural (pristine), Degraded, and Restored (prior to fire), and not accounting for wildfire; No burn – natural and No burn - degraded.

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

In addition to the impact of degradation, peatland NEE + CH_4 fluxes are also sensitive to the increasing pressures of climate-mediated drying and associated increases in peat carbon loss from combustion[10]. By aggregating a global dataset of fire perimeters from 2001–2021 (FIRED[44]; Fig. S1), we calculated the average burn rate (percent of land area burned per year) for boreal and temperate non-permafrost regions over the last two decades (Methods). Average burn rate varied between 0.0001 and 1.48 % yr^{-1} amongst boreal and temperate ecoregions (Table S1), with a spatially weighted average of 0.35 % yr^{-1}, equivalent to a FRI of 290 years. Assessment of the relationship between peatland (histosol) areal coverage[3] and burn rate found no significant trends (Fig. ED2, S2 and S3), suggesting that peatland cover does not exert a strong control over regional area burned. Compilation of national inventories found that degradation due to drainage for agriculture, horticulture, and forestry varies between <1 and 54 % of peatland area per country[34] and the proportion of total drained northern peatland area is ~7 % (26.1 Mha; [21]). These data were used to evaluate the current state of the boreal and temperate non-permafrost peatland system.

At the broadest scale, without accounting for future climate change impacts to peatlands or wildfire regimes, we estimate that the total NEE + CH_4 flux for boreal and temperate non-permafrost peatlands is a small net carbon sink (filled dots Fig. 2), however, the system becomes a net carbon source given an annual average peatland burn rate of more than 0.77 % based on the current estimates of drained peatland area (Fig. 2a). Accordingly, and important for regional carbon balances, a greater percentage of degraded peatlands reduces the burn rate required to switch the system from a net carbon sink to a net carbon source by 0.05 % yr^{-1} per additional 1 % degraded peatland area.

Similarly, increased peat carbon loss from combustion reduces the carbon sink strength and may contribute to switching the system to a net source. Increasing the average peat carbon loss from combustion in pristine peatlands to represent a moderate degree of climate change drying (1.5 kg C m^{-2} added to the original distribution; Methods) reduces the annual burn rate required to switch from a carbon sink to source to 0.55 % (Fig. 2b). This equates to a required lengthening of the average FRI by ~50 years to maintain active net carbon sequestration at a landscape level. Further, there is a strong interactive effect of percent degraded and peat carbon loss on NEE + CH_4 (Fig. 2c). Using the spatially weighted average burn rate of 0.35 % yr^{-1}, NEE + CH_4 fluxes are sensitive to changes in percent degraded, where a relatively small reduction in percent degraded (e.g., by one-third from 15 to 10 %) via active restoration counteracts potential increases in average peat carbon loss from combustion caused by climate-mediated drying.

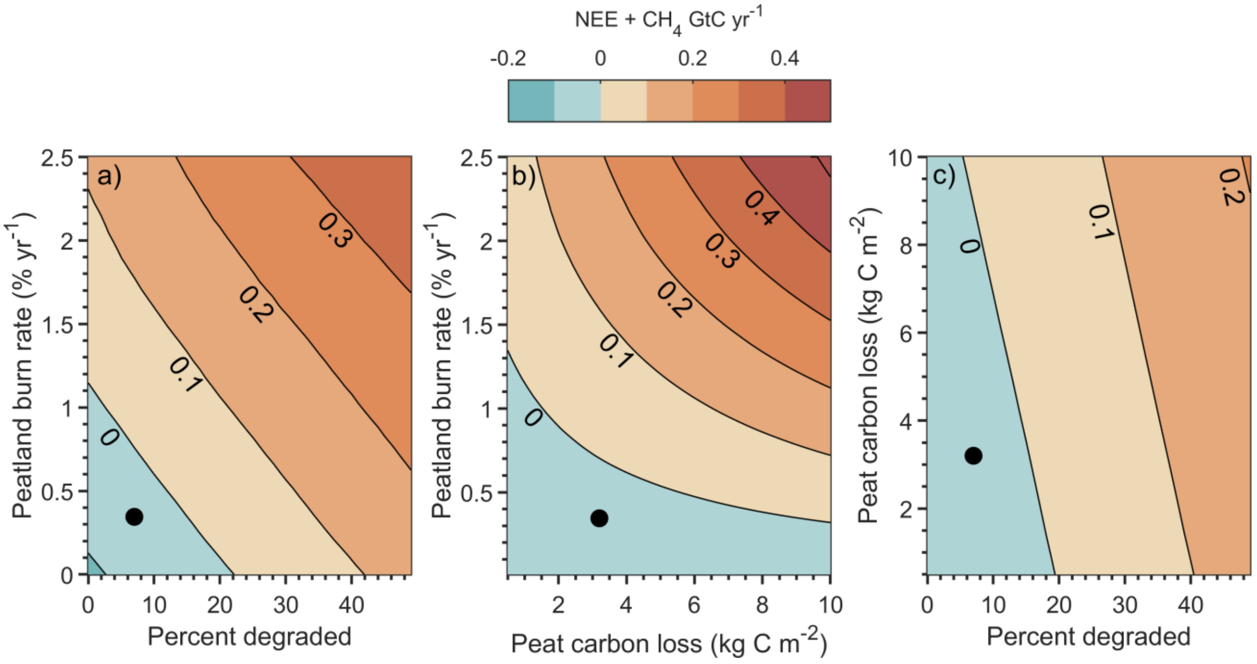

Fig. 2. The interactive effect of fire regime changes and degraded peatland area, on NEE + CH_4 (GtC yr^{-1}). a) Peatland burn rate and percent degraded, where peat carbon loss is weighted based on percent degraded. b) Peatland burn rate and peat carbon loss, where percent degraded is held constant at 7 %. c) Peat carbon loss and percent degraded, with a 0.35 % (spatially-weighted average) burn rate. Filled dots represent the current boreal and temperate non-permafrost peatland system in the NEE and CH_4 flux phase space. Axes do not show zero where a zero value results in a no-data point.

The future of the northern peatland carbon sink

To illustrate the impact of peatland degradation status and climate change on the magnitude of the peatland carbon sink we evaluated cumulative annual net fluxes from our NEE + CH_4 simulations. We developed scenarios that combine different peatland degradation and climate change factors and assessed the impact on total carbon sequestration (or emission) by 2050 and 2100 (Methods). Scenarios include i) No burn, ii) Current state, iii) Restoration, iv) Increased burn rate, v) Increased (burn) severity, and vi) Full climate change (increased burn rate and burn severity).

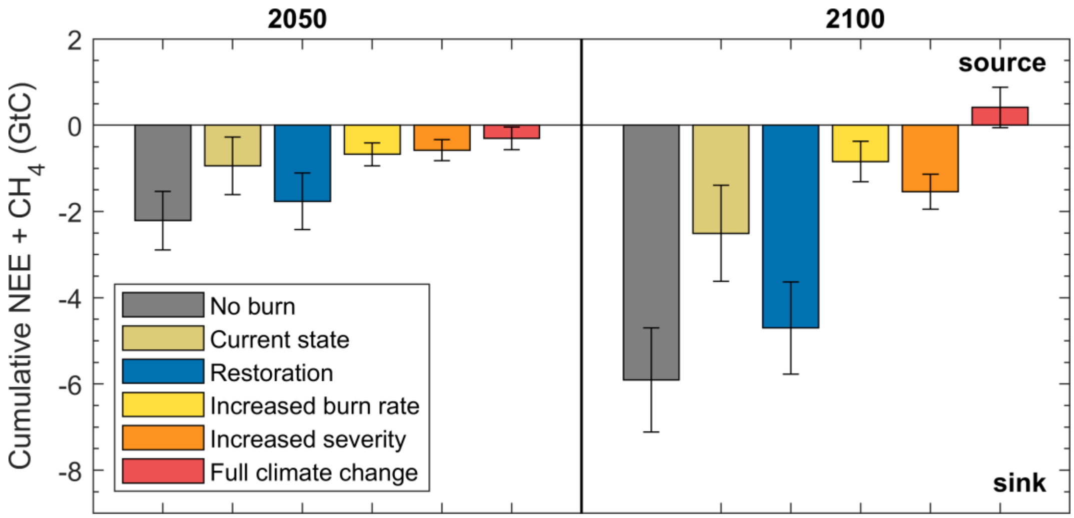

Fig. 3. Cumulative NEE + CH_4 flux (GtC) for boreal and temperate non-permafrost peatlands in 2050 and 2100. Negative values represent a carbon sink while positive values represent a carbon source. Scenarios include: Current state, No burn (Current state with 0 % burn rate), Restoration (100 % of degraded peatlands restored), Increased burn rate (annual rate doubling by 2100), Increased severity (additional 1.5 kg C m^{-2} loss across all peatland states), and Full climate change (increased burn rate and severity). Error bars (±1 sd) represent the uncertainty estimated via Monte Carlo simulations using distributions of burn rate and NEE + CH_4.

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

Increasing peatland burn rate (linear increase to 0.7 % by 2100) and increasing burn severity (+1.5 kg C m^{-2} peat carbon loss) decrease the peatland carbon sink by similar amounts by 2050 with a 0.25 and 0.36 GtC reduction relative to the Current scenario, respectively. However, the modelled burn rate increase throughout the remainder of the century results in a large decrease in the carbon sink strength in the Increased burn rate scenario by 2100, reducing the total carbon sequestration to a sink of 0.88 GtC, a 65 % decrease compared to the Current scenario (-2.5 GtC). Concerningly, when the impacts of climate change are combined (Full climate change scenario) the system shows a potential switch from a carbon sink to a carbon source, with a mean estimated source of 0.4 GtC to the atmosphere by 2100. The acceleration of carbon release from boreal and temperate non-permafrost peatlands and associated diminishment of the strength of the carbon sink over the coming decades has critical implications for global climate change and emissions targets.

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

This study highlights the resilience of pristine northern peatland ecosystems to wildfire, with natural peatlands returning to a net carbon sink in most of our simulations across the range of fire severity and post-fire dynamics. Conversely, we demonstrate unequivocally that degraded peatlands are responsible for the largest peatland carbon emissions[19,20,31]. We show that the restoration of degraded peatlands prior to fire greatly reduces long-term emissions[33]. Our results add to the growing literature base that suggests climate and land-use change increase the vulnerability of peatland ecosystems and their carbon stocks to fire, with significant and far-reaching ecological, hydrological, and societal consequences[34,35].

While future anthropogenic fossil fuel emissions can be curbed, the climatic changes already induced by rising atmospheric CO_2 concentrations will likely continue to increase peatland wildfire emissions over the coming century, reducing the strength of the peatland carbon sink. We show that although the peatland carbon sink is currently resilient, changes in degraded peatland area, average burn rate (FRI) and peat burn severity may lead to climate neutrality or net carbon release. Climate-mediated peatland drying across the spectrum of peatland condition[27,29] could contribute to increases in peatland burn rate[36] and peat carbon loss via enhanced burn severity[10] in line with the increasing availability of critically dry peatland fuels[9]. Forested peatlands (natural or managed) may be more prone to positive (amplifying) ecohydrological feedbacks that promote high severity smouldering fire[37], when compared to arable peatlands in northern regions, however, the vulnerability of peatlands to wildfire under different management regimes is currently relatively unstudied.

To maintain the northern peatland carbon sink function, decreases in the area of degraded peatland through active peatland restoration must occur to counteract potential increases in average peat carbon loss due to climate-mediated drying. Our restoration scenario (representing the restoration of all degraded peatlands) resulted in an estimated increase in the carbon sink by almost 90 % by 2100 compared to the current scenario. Despite the hypothetical nature of our restoration scenario, it serves to support research highlighting the important role peatlands can play in reducing global emissions if they are protected[38] and restored[39] appropriately. We also strongly advocate for better management of carbon-rich ecosystems alongside behavioural changes to stop accidental and unnecessary ignitions[40] especially areas with a high proportion of degraded peatlands (e.g., Europe)[11].

On a regional level we provide evidence of the importance of accurately measuring (degraded) peatland area, as well as burn rate, since these factors will affect the ability of countries/regions to account for emissions and potentially, to achieve emissions targets. The proportion of peatlands affected by land use change varies considerably between countries and regions but can be substantial (<1 to ~50 % degraded[41]). While there are likely differences in the ignition potential of different peatland land-uses[19] there is a scarcity of these data in the literature. Peatland type and landscape position have been found to impact burn rate[32] and fire severity[42], yet peatlands are often misclassified in fire risk, spread, and emissions models[43], highlighting the need to improve peatland mapping for use alongside remotely sensed fire products (e.g.,[44]). Appropriate accounting of carbon emissions from peatlands, accounting for wildfire, may guide national/regional restoration and conservation strategies (e.g., the UK[45]).

Interdisciplinary collaborations will be crucial to accurately represent the northern peatland carbon balance in earth system models and ensure community- to international-level climate policies include important peatland processes, such as fire, in their strategies to maintain the impacts of climate change within liveable bounds. While remote-sensing applications, such as FIRED[44], have enabled consistent burn rate mapping across large regions, the limited precision and consistency of peatland type and carbon stock maps creates challenges for further reducing the uncertainty surrounding estimates of the strength of the northern peatland carbon sink[38]. Further, our carbon sink estimates don’t account for fluvial export of carbon, nor the anthropogenic additions/removals of biomass on agricultural peatlands. Data corresponding to methane emissions in different peatland types immediately post-fire e.g.,[22,23] would further constrain estimates of the peatland carbon sink.

The direction and magnitude of the peatland-climate feedback will be driven by the combined effects of peatland degradation and restoration, and the global emissions pathway that will influence rates of climate-induced drying[27] and changes in burn rate[26]. Northern peatlands have regulated global climate over the Holocene but if the predicted increases in peat burn severity and fire activity outweigh carbon sequestration from peatland expansion in high-latitude regions[47], the northern peatland system will become a shrinking carbon sink and a potential future carbon source, exacerbating the rapidly closing window of time to avoid the most severe impacts of global climate change. Our scenario results found that increasing burn rate and peat burn severity drastically reduced the amount of carbon sequestered in peatlands, but overall the system maintained a carbon sink status in 2050. However, the continued and compounding impacts of climate change resulted in an estimated small net carbon source to the atmosphere by boreal and temperate non-permafrost peatlands by 2100. Notably this estimate does not account for increased peatland tree growth stimulated by drier conditions[10], however, given the positive correlation between tree size and burn severity[10] and the dominance of long-term carbon storage in peat rather than above-ground vegetation[48], it is unlikely that increases in above-ground biomass will translate into significant increases in carbon storage over long (>1 FRI) time periods. The likely reduction in peatland carbon sink strength will create further challenges to remaining below critical global climate targets.

Against the global backdrop of increases in burn rate and extreme wildfire weather[26], integrated regional wildfire management solutions are urgently required to mitigate severe climatic and societal impacts of peatland wildfire[36,37]. In regions with higher proportions of peatland degradation we find that a strong trade-off with burn rate (i.e., large investments in direct fire suppression) is required to preserve the critical climate regulation function of peatlands. Where this balance is not maintained peatland wildfire emissions may represent an under-appreciated source component in carbon accounting that could be detrimental to achieving emissions targets. We demonstrate here that, despite notable impacts of peatland burn rate and burn severity, peatland restoration represents a large opportunity to minimize impacts to the boreal and temperate peatland carbon sink over the coming century when accounting for peatland wildfire emissions. Our results suggest an immediate need to start including active restoration of degraded peatlands as a cost-effective tool to support the mitigation of extensive carbon emissions and detrimental impacts on human health.

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Competing Interests

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

Author Contributions

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

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Extended Data

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

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

Region	**Biome**	**Total area (10^6 km^2)**	**Burned area (10^6 km^2)**	**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

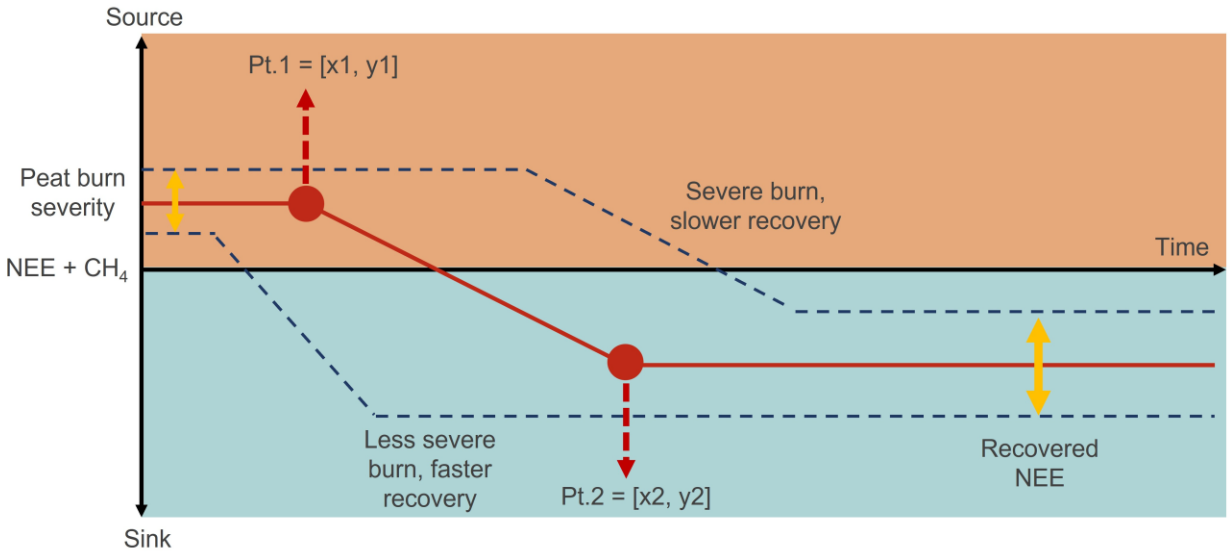

Figure ED1. Conceptual diagram of the modelling design developed to incorporate peat carbon loss from wildfire (peat burn severity) and post-fire carbon dynamics (recovery rate and recovered net ecosystem exchange (NEE)) in peatland GHG emissions. Where y1 represents the NEE + CH_4 of a burned peatland, x1 represents the time lag between wildfire and the initiation of post-fire recovery, x2 represents the time at which “recovered” NEE is achieved and y2 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.

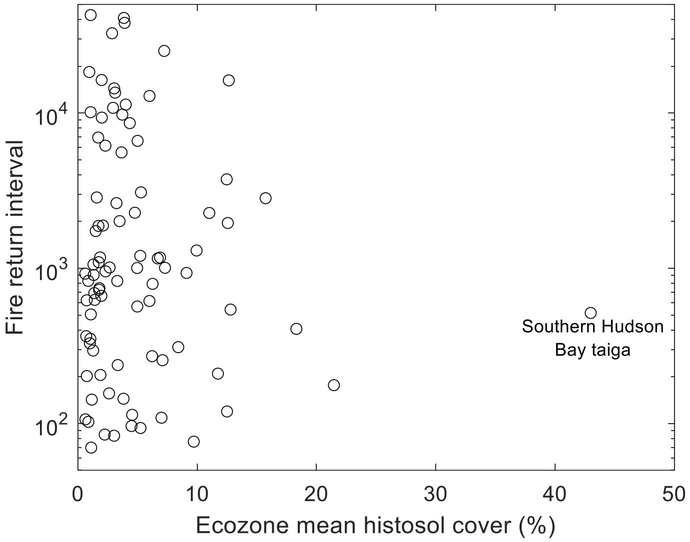

Figure ED2. Fire return interval (100/(burn rate)) per ecoregion, and mean ecoregion histosol cover. The Southern Hudson Bay taiga ecoregion is highlighted as the region with the highest histosol cover (~43%).