Don't Burn Up: Northern peat fire emissions and the remaining carbon budget

Sophie Wilkinson (sophie.wilkinson@utoronto.ca)
University of Toronto https://orcid.org/0000-0002-4043-6277
Roxane Andersen
University of Highlands and Islands
Paul Moore
McMaster University https://orcid.org/0000-0003-1924-1528
Scott Davidson
University of Plymouth
Gustaf Granath
Department of Ecology and Genetics, Uppsala University https://orcid.org/0000-0002-3632-9102
J Waddington
McMaster University https://orcid.org/0000-0002-0317-7894

Article

Keywords: climate change, emissions targets, peatland, wildfire, post-fire dynamics, carbon accounting, ecosystem restoration

Posted Date: August 15th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1909843/v1

Don't Burn Up: Northern peat fire emissions and the remaining carbon budget

Wilkinson, S. L.*[1,2], Andersen, R.[3], Moore, P. A.[1], Davidson, S. J.[4], Granath, G.[5], & Waddington, J. M.[1]

*Corresponding author sophie.wilkinson@utoronto.ca

Affiliations:
[1] School of Earth, Environment and Society, McMaster University, L8R4L8, Canada.
[2] Institute of Forestry and Conservation, University of Toronto, M5S 3B3, Canada.
[3] Environmental Research Institute, University of the Highlands & Islands, Thurso, KW14 7JD, UK.
[4] School of Geography, Earth and Environmental Sciences, University of Plymouth, PL4 8AA, UK.
[5] Department of Ecology and Genetics, Uppsala University, 752 36, Sweden.

SLW 0000-0002-4043-6277
RA 0000-0002-7782-795
PAM 0000-0003-1924-1528
SJD 0000-0001-8327-2121
GG 0000-0002-3632-9102
JMW 0000-0002-0317-7894

Keywords:
climate change, emissions targets, peatland, wildfire, post-fire dynamics, carbon accounting, ecosystem restoration

Abstract:

Despite estimates of climate target's remaining carbon budget (RCB) informing critical policy, most climate projections do not account for peatland ecosystem processes, including the contribution of current or future peatland wildfires to global carbon emissions. Here, we provide the first estimate of the carbon emissions associated with non-permafrost northern peatlands that specifically includes both wildfire combustion and post-fire carbon dynamics. The inclusion of wildfire reduced the carbon sink from -59.5 ± 32.2 to -17.9 ± 45.7 g C m^{-2} yr^{-1} in natural (pristine) peatlands while degraded peatlands represented a consistent source of carbon (218.6 ± 48.1 g C m^{-2} yr^{-1}). We find that small increases in average burn severity or peatland area burned (from 0.5 to 0.8 % yr^{-1}) could tip northern peatlands from a net carbon sink to a net source, illustrating the critical importance of peatland wildfire emissions and their accounting to the RCB for global climate targets.

Peatlands store approximately one-third of the 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], actively 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 estimates of climate target's remaining carbon budget (RCB) informing critical policy and funding decisions[11], most earth system models and climate projections do not account for peatland ecosystem processes[12], but some advances are now being made[13]. As atmospheric greenhouse gas concentrations rapidly accelerate towards levels that will negate the possibility of limiting global warming to less than 1.5 or 2^{o}C [14] it is imperative to quantify the contribution of peatlands in the context of the RCB. While estimates of the contribution of peatland drainage to global GHG emissions have been made[15,16], no such evaluation has been conducted for, or includes, peatland wildfires.

Northern non-permafrost peatlands have developed over the last 7-12 millennia, experiencing recurrent wildfire disturbance[17]. Carbon emissions from pristine peatland wildfires can vary considerably, however, they typically average 1–3 kg C m^{-2} [10,18,19]. These relatively small peat combustion carbon losses can be re-accumulated within 10 to 30 years post-fire[20], enabling peatlands to remain a net carbon sink over typical fire-free intervals[21]. Conversely, peatland degradation, such as peatland drainage, can enhance 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[10,19,22,23]. Given that >25 Mha (7 %) of boreal and temperate peatlands have been drained for anthropogenic use[24], with some regional or national estimates exceeding 50 % [25], these degraded peatlands represent high risk areas where wildfire could lead to large carbon emissions.

The differences in carbon dynamics between pristine and degraded (such as drained) peatland wildfires are exacerbated when determining their net ecosystem carbon budget (NECB) by examining post-fire carbon dynamics. Alterations to CO_2 and CH_4 (methane) fluxes immediately after fire affect the short-term carbon balance[26-28] while post-fire vegetation recovery controls the long-term carbon balance[8,20,29]. Evidence suggests that the greater burn severity in degraded peatlands increases the potential for ecosystem regime shifts[8] and a reduction in the magnitude of the "recovered" carbon sink function, further increasing the carbon impact of peatland wildfires and our capacity to maintain current CO_2 emissions within the RCB. As such, the inclusion of peatland degradation and post-fire carbon dynamics are paramount for the accurate evaluation of northern peatland wildfire carbon emissions.

Rapid changes to regional wildfire regimes are compounding the impacts of land-use change on peatland wildfire interactions. In the boreal zone, area burned[30] and the frequency of extreme fire weather conditions[31] are increasing as enhanced atmospheric moisture demand is leading to drier wildfire fuels, particularly in peatland ecosystems[32]. Similarly, in the temperate zone increased wildfire occurrence has been associated with severe droughts[33], and long-term drying has been observed in peatlands[34]. Increased lightning occurrence in conjunction with reduced snowpacks and multi-year droughts are predicted to further promote large fire years[35]. Such combinations of climate change-mediated stressors in northern peatlands, along with pervasive peatland degradation, are likely to increase peatland area burned, peat burn severity, and associated carbon losses[9,10]. Yet, and despite, evidence that individual northern peat fires can produce teragrams of carbon emissions[19,22,36], the current and future contribution of northern peatland fires to global carbon emissions is unclear and poorly accounted, if at all, in both national inventories and RCBs[14,37]. Hence, here we provide the first estimate of the contribution of northern peatland wildfire and post-fire dynamics to global carbon emissions in the context of current climate change targets.

Empirical modelling of peatland Net Ecosystem Carbon Balance

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 carbon balance (NECB) of northern peatlands over time, integrating post-fire carbon dynamics and averaging over a distribution of fire free intervals (Table ED1, Methods). The inclusion of peat combustion carbon emissions and post-fire carbon dynamics reduced the mean (sd) NECB sink strength from -59.5 (32.2) g C m^{-2} yr^{-1} (No Burn) to -17.9 (45.7) g C m^{-2} yr^{-1} in natural (pristine) peatlands experiencing fire, evidencing the high resistance of the peatland carbon sink function. Across the variability in wildfire return interval and the impacts of the fire (i.e., severity, recovery rate) the NECB of degraded peatlands remained a consistent source of carbon at 218.6 (48.1) g C m^{-2} yr^{-1}. Meanwhile, the restoration of peatlands prior to fire mitigated extensive carbon emissions, yet these peatlands remained a small source of carbon with an average NECB of 27 (45.0) g C m^{-2} yr^{-1} (Fig. 1). As such, our modelling indicates that excluding peatland wildfire from peatland NECB calculations results in a misrepresentation of peatland carbon balance and may impact regional to national emissions budgets, especially in fire-prone areas with a high proportion of degraded peatlands.

Our empirical approach accounts for uncertainty in the magnitude of peat combustion emissions, the fire return interval, the rate of recovery, and the initial and final recovered net ecosystem exchange (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 NECB in these scenarios. To further constrain peatland NECB 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.

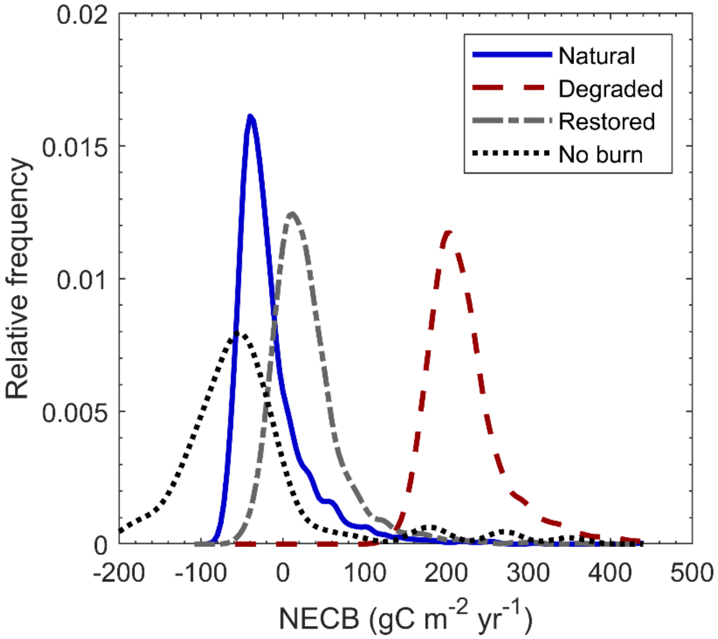

Fig. 1. Distribution of Net Ecosystem Carbon Balance (NECB) derived from Monte Carlo simulation model outputs accounting for variation in the magnitude of peat combustion emissions, the fire return interval, the rate of recovery, and the initial and final recovered carbon balance for peatlands. Scenarios include not accounting for wildfire (No burn), natural (pristine), degraded, and restored (prior to fire).

Effect of degradation and climate-induced drying on peat fire emissions

In addition to the impact of degradation, peatland NECB is also sensitive to the increasing pressures of climate-mediated drying and associated increases in smouldering combustion loss. By aggregating a global GIS dataset from 2001–2021 (FIRED[38]), 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 0.05 and 1 % yr^{-1} amongst our six regions (Table ED2), with a spatially weighted average of 0.5 % yr^{-1}. Assessment of national inventories found that degradation due to drainage for agriculture, horticulture, and forestry varied between <1 and 54 % of peatland area per country[25].

At the broadest scale, without accounting for future climate change impacts to peatlands or wildfire regimes, we estimate that the total NECB for boreal and temperate peatlands is a small net sink, however, they become a net source of carbon given an annual average peatland area burned of more than 0.8 % based on the current estimates of drained peatland area of ~7 % (26.1 Mha; [24]) (Fig. 2a). Accordingly, and important for regional carbon balances, a greater percentage of degraded peatlands reduces the peatland area burned required to switch the system from a net carbon sink to a net carbon source by 0.04 % yr^{-1} per 1 % degraded peatland area.

Similarly, increased peat combustion carbon loss reduces the carbon sink strength of northern peatlands and may contribute to switching the system to a net source. Increasing the average carbon loss in pristine peatlands to represent a moderate climate change drying scenario (+1.5 kg C m^{-2}; [10]) reduces the annual burned area required to switch from a sink to source from 0.8 % to 0.6 % (Fig. 2b). This equates to a required lengthening of the fire free interval from 125 to 160 years to maintain active carbon sequestration. Further, there is a strong interactive effect of percent degraded and peat carbon loss on NECB (Fig. 2c). Using the spatially weighted average burn rate of 0.5 % yr^{-1}, NECB is sensitive to changes in percent degraded, where relatively small reductions in percent degraded (e.g., from 15 to 10 %) via active restoration counteracts potential increases in average peat carbon loss from smouldering combustion caused by climate change.

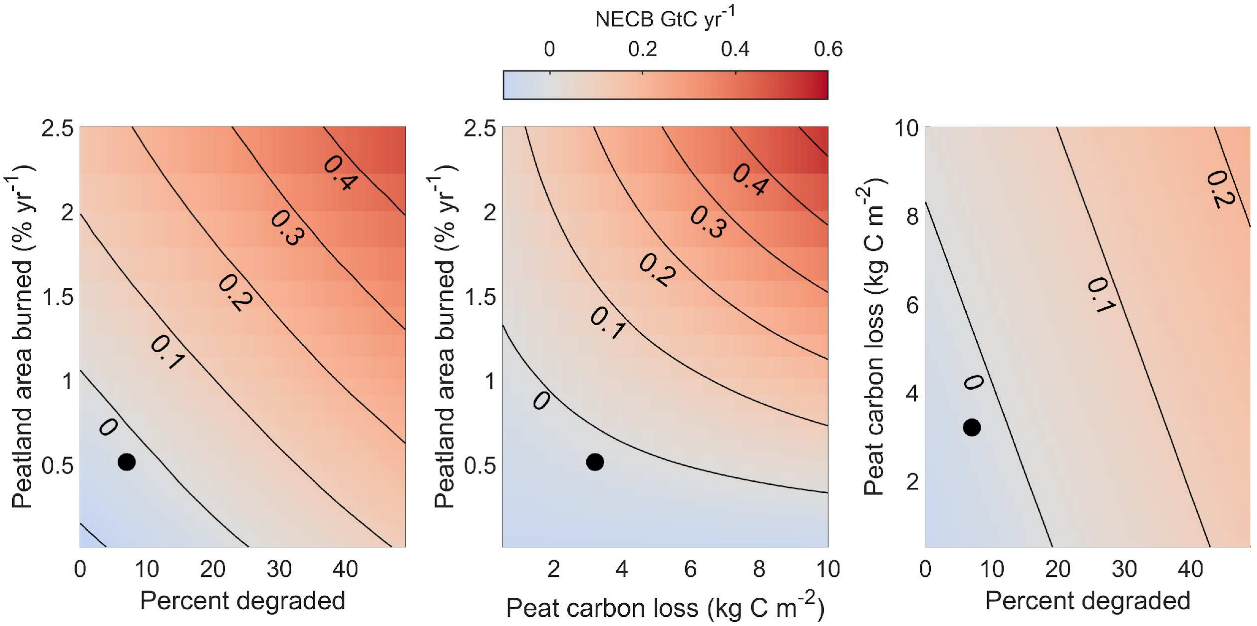

Fig. 2. The interactive effect of fire regime changes (peatland area burned; % yr^{-1} and peat carbon loss; kg C m^{-2}) and the percent of peatland area that is degraded, on NECB (Gt C yr^{-1}). a) Peatland area burned and percent degraded, where peat carbon loss is weighted based on % degraded (i.e., higher peat carbon loss with greater % degraded). b) Peatland area burned and peat carbon loss, where percent degraded is held at 7 %. c) Peat carbon loss and percent degraded, given a

mean annual area burned of 0.51 % (spatially weighted average burn rate). The black filled dots represent the current northern non-permafrost peatland system in the NECB phase space.

Peatlands contribution to the remaining carbon budget

Lastly, we illustrate the importance of peatland wildfire emissions when incorporating peatland processes into earth system models. We contextualise the estimated carbon emissions in the 1.5°C and 2.0°C RCBs under a low-emissions (RCP2.6) and moderate-emissions (RCP4.5) scenario by showing the cumulative median NECB for three simplified peatland scenarios (No burn, Natural, Degraded, and Restored, all 100 %).

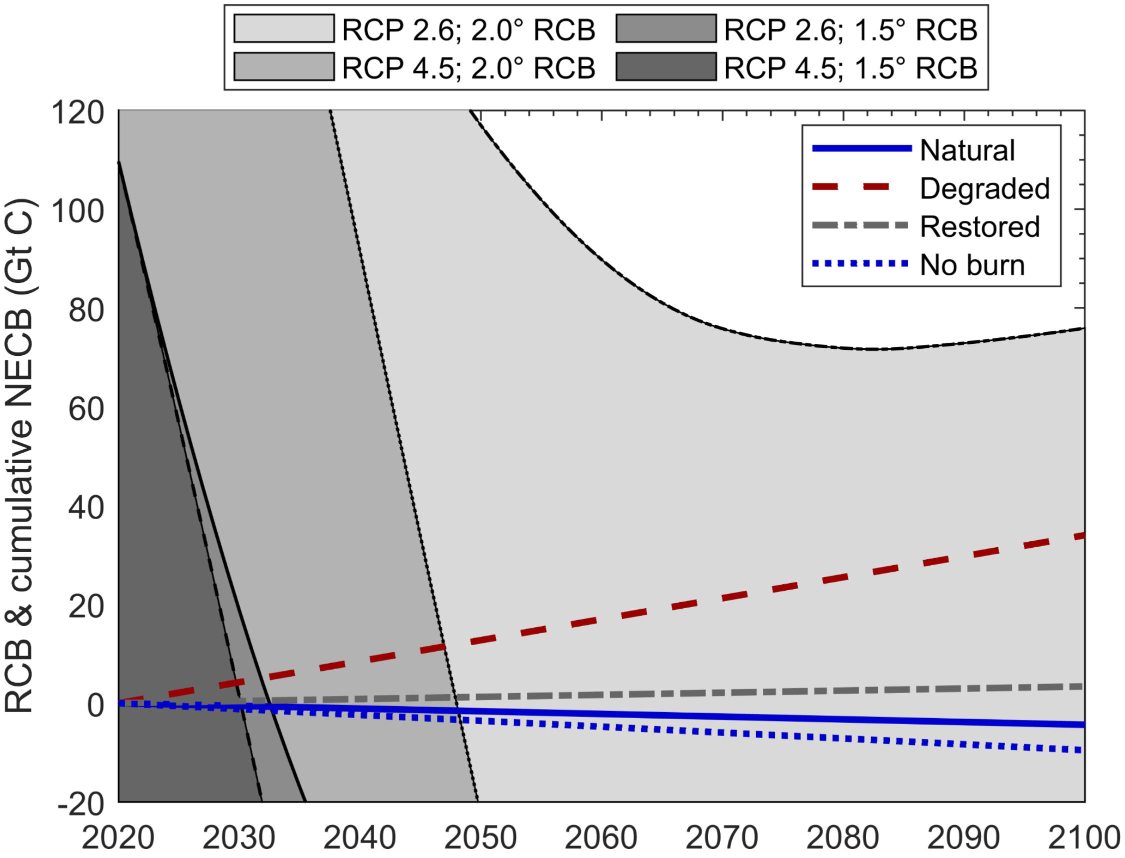

Figure 3. The cumulative median NECB for simplified scenarios of natural (blue solid), degraded (red dashed), restored (gray dot-dash), and no burn (blue dot) peatlands for all northern non-permafrost peatland area over the 21st century, mapped onto the RCB for low- and moderate-emissions scenarios (RCP 2.6 and 4.5, respectively) and 1.5°C and 2°C average temperature change targets. The difference between the intersections of the peatland NECB lines and the right-most line of each RCB shows the impact of different peatland emissions scenarios on the time-taken, or year in which, each RCB will be filled and the associated climate change target will be missed.

The inclusion of peatland wildfire emissions in earth system models will affect the estimates of RCB over the next century. The difference between the No burn and Natural scenarios shows the potential overestimation of impacts on RCBs (>5 GtC by 2100) if wildfire emissions are not accounted for. The impacts of peatland wildfire emissions and their inclusion in RCB calculations is limited by the pace at which society is consuming the 1.5°C RCB since the budget is exhausted by 2035 in both the low- and moderate-emissions scenario. However, the considerable difference (>30 GtC by 2100) in cumulative emissions of Degraded and Restored (simplified, 100% area) scenarios illustrates the long-term benefit of peatland restoration. Further, we show that reducing anthropogenic emissions in line with the low-emissions scenario (RCP2.6) creates a buffer where peatland wildfire emissions constitute minimal change in the RCB over the next century. Therefore, the inclusion of peatland wildfire emissions in earth system models and global carbon accounting is important for the accurate calculation of timelines of the point at which limiting global warming to 1.5°C or 2°C becomes unachievable.

Assessing the importance of peatland restoration and conservation for the remaining carbon budget

This study highlights the strong 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 within temperate and boreal regions are responsible for the majority of peatland wildfire carbon emissions, indicating that the restoration of degraded peatlands prior to fire greatly reduces long-term emissions, even potentially reinstating the long-term net carbon sink function. 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[39-41]. The impacts of wildfire can alter the complex feedback mechanisms that govern ecosystem resilience and underpin the interaction between peatlands and climate, such as the fate of “irrecoverable” carbon that, once lost to the atmosphere, will not be re-accumulated within timeframes relevant to the current climate crisis[42]. Consequently, our study further emphasises that the protection and conservation of pristine peatlands should be a priority, and that new peatland drainage and degradation should be strongly avoided[16].

While anthropogenic fossil fuel emissions can be curbed, due to the climatic changes already induced by rising atmospheric CO_2 concentrations, peatland wildfire emissions will likely continue to increase in line with the increasing availability of critically dry peatland fuels[9]. Indeed, while we must restore and rewet degraded peatlands, climate-mediated widespread peatland drying across the spectrum of peatland condition[32,34] could contribute to increases in peat carbon combustion emissions, via enhanced smouldering combustion[10]. In regions where climate-mediated drying is more prevalent there is high potential for the initiation or strengthening of ecohydrological feedbacks that promote high severity fire[43], along with detrimental effects on air quality and human health[44]. We show that such climate change impacts to average peat combustion carbon loss would push the system dangerously close to becoming a net carbon source. To maintain the northern peatland carbon sink function, decreases in the area of degraded peatland (i.e., peatland restoration) must occur to counteract potential increases in average peat carbon loss due to climate-mediated drying. Further, despite management interventions and protection to maximise landscape resilience, across western European peatlands, wildfires are predominantly ignited by people, accidentally or otherwise[45]. As the climate changes and wildfire risks increase, we strongly advocate for better management of carbon-rich ecosystems alongside behavioural changes to stop accidental and unnecessary ignitions.

The enhancement of tree growth rates or shrubification due to drying increases the above-ground carbon stock but may lead to runaway drying effects[43]. Given the potential for peatlands to undergo an ecosystem regime shift following severe wildfire[8], often associated with compounding disturbance such as drainage or drying[46], our approach provides a conservative estimate of the future impact of wildfire on NECB. While we assume recovered net ecosystem CO_2 exchange is always negative (i.e., carbon sink), ecosystem regime shifts cause divergence from typical recovery trajectories further depleting long-term peatland carbon stocks[8]. In combination with increases in extreme fire weather days[31], repeated burns at shorter intervals or wildfires affecting areas previously thought of as fire refugia may become more common[47]. We show that while the peatland carbon sink is currently resilient, small changes in average fire free interval (peatland area burned per year) may lead to climate neutrality (NECB ~0) or net carbon emission.

On a regional level we evidence the importance of accurately measuring (degraded) peatland area, as well as area burned, since these factors will affect the ability of countries/regions to account for emissions and potentially, to achieve targets. The interaction between land-use change and peatlands can be substantial but varies considerably between countries and regions (<1 to 54% peatland degradation; [25]). While there are likely differences in the ignition potential of different peatland land-uses[23] there is a scarcity of these data in the literature. Peatland type and landscape position have been found to impact ignition and fire severity[48], yet peatlands are often misclassified in fire risk, spread, and emissions models, highlighting the need to improve peatland mapping for use alongside remotely sensed fire products (e.g.,[49]). Appropriate accounting of carbon emissions may guide national/regional restoration and conservation strategies (e.g., UK; [50]). However, and given that the majority of peatlands in tropical regions (that were outside the scope of this study) are degraded[51], we also urge the peatland science community to gather data on the NECB of tropical peatlands, accounting for fire across the spectrum of degradation for inclusion in global carbon accounting.

The direction and magnitude of the peatland-climate feedback will be driven by the combined effects of peatland degradation and restoration, climate-induced drying, and the global emissions pathway. The nature of the inclusion of boreal and temperate non-permafrost peatland wildfire emissions in earth system models affects estimates of the time taken to exceed climate change targets. We show that not including peatland wildfire (No burn scenario) over-estimates the peatland carbon sink, and subsequent extension of time to exceed the RCB, and that the Natural scenario results in only a marginal increase in time to exceedance. While the strong power of peatland restoration over the centurial timescale is supported[52], as society rapidly consumes the RCB there is a limited capacity for the benefits of peatland restoration (and return of carbon sink function) to extend the time taken to exceed the RCB, in particular for targets of 1.5°C of average warming. Further, if the predicted increases in peat burn severity[9,10] and fire activity in some peatland-dominated regions[31] outweigh carbon sequestration from moss expansion in northern regions[53], the northern peatland system will become a shrinking carbon sink and potential future carbon source, exacerbating the rapidly closing window of time to avoid the most severe impacts of global climate change. Hence, our study further supports the overwhelming evidence to immediately curb anthropogenic emissions enough to remain below these critical climate targets.

Against the global backdrop of increases in risks of extreme wildfires and shrinking RCBs, integrated regional wildfire management solutions are urgently required to mitigate severe climatic and societal impacts of peatland wildfire[40,41]. 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 represent an under-appreciated component in carbon accounting that could be detrimental to achieving climate targets. We demonstrate here that there is an immediate need to start including active restoration of degraded peatlands as a cost-effective tool to support the mitigation of carbon emissions and impacts on human health. Interdisciplinary collaborations will be crucial in accurately representing the global peatland carbon balance in earth system models and ensuring community- to international-level climate policies include important peatland processes, such as fire, in their strategies as we fight to maintain the impacts of climate change within liveable bounds.

Acknowledgements

The research published in this paper is part of the Boreal Water Futures project, which is funded by the Global Water Futures programme of the Canada First Research Excellence Fund. Funding was also provided by the NSERC/Canadian Forest Service Canada Wildfire Strategic Network

Competing Interests

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

Author Contributions

Wilkinson: Conceptualisation, data curation, formal analysis, methodology, visualization, writing – original draft, writing – review & editing. Andersen: Conceptualisation, methodology, visualization, writing – review & editing. Moore: Data curation, formal analysis, methodology, writing – review & editing. Davidson: Data curation, writing – original draft, writing – review & editing. Granath: Data curation, writing – original draft, writing – review & editing. Waddington: Conceptualization, funding acquisition, methodology, supervision, writing – review & editing.

References

1. Yu, Z., Loisel, J., Brosseau, D.P., Beilman, D.W., and Hunt, S.J. 2010. Global Peatland Dynamics since the Last Glacial Maximum. *Geophysical Research Letters* 37 (13): L13402. https://doi.org/10.1029/2010GL043584
2. Xu, J., Morris, P.J. Liu, J. and Holden, J. 2018. PEATMAP: Refining Estimates of Global Peatland Distribution Based on a Meta-Analysis. *Catena,* 160: 134–40. https://doi.org/10.1016/j.catena.2017.09.010
3. Hugelius, G., Loisel, J., Chadburn, S., Jackson, R.B., Jones, M., MacDonald, G., Marushchak, M. et al. 2020. Large Stocks of Peatland Carbon and Nitrogen Are Vulnerable to Permafrost Thaw. *Proceedings of the National Academy of Sciences of the United States of Americ*a, 117 (34): 20438–46. https://doi.org/10.1073/pnas.1916387117
4. Frolking, S. and Roulet, N.T. 2007. Holocene Radiative Forcing Impact of Northern Peatland Carbon Accumulation and Methane Emissions. *Global Change Biology*, 13 (5): 1079–88. https://doi.org/10.1111/J.1365-2486.2007.01339.X
5. Gallego-Sala, A.V., Charman, D.J., Brewer, S., Page, S.E., Prentice, I.C., Friedlingstein, P., Moreton, S. et al. 2018. Latitudinal Limits to the Predicted Increase of the Peatland Carbon Sink with Warming. *Nature Climate Change, 2018 8:10* 8 (10): 907–13. https://doi.org/10.1038/s41558-018-0271-1
6. Ferretto, A., Brooker, R., Aitkenhead, M., Matthews, R. and Smith, P. 2019. Potential Carbon Loss from Scottish Peatlands under Climate Change. *Regional Environmental Change,* 19 (7): 2101–11. https://doi.org/10.1007/S10113-019-01550-3/TABLES/2
7. Loisel, J., Gallego-Sala, A.V., Amesbury, M.J., Magnan, G., Anshari, G., Beilman, D.W., Benavides, J.C., et al. 2020. Expert Assessment of Future Vulnerability of the Global Peatland Carbon Sink. *Nature Climate Change 2020 11:1* 11 (1): 70–77. https://doi.org/10.1038/s41558-020-00944-0
8. Kettridge, N., Turetsky, M.R., Sherwood, J.H., Thompson, D.K., Miller, C.A., Benscoter, B.W., Flannigan, M.D., Wotton, B.M. and Waddington, J.M. 2015. Moderate Drop in Water Table

Increases Peatland Vulnerability to Post-Fire Regime Shift. *Scientific Reports,* 5: 8063. https://doi.org/10.1038/srep08063

9. Turetsky, M.R., Benscoter, B.W., Page, S.E., Rein, G., Van Der Werf, G.R., and Watts, A. 2015. Global Vulnerability of Peatlands to Fire and Carbon Loss. *Nature Geoscience 8:1* 8 (1): 11–14. https://doi.org/10.1038/ngeo2325.2014b
10. Wilkinson, S. L., Moore, P.A., Flannigan, M.D., Wotton, B.M. and Waddington, J.M. 2018. Did Enhanced Afforestation Cause High Severity Peat Burn in the Fort McMurray Horse River Wildfire? *Environmental Research Letters,* 13 (1): 014018. https://doi.org/10.1088/1748-9326/AAA136
11. Goodwin, P., Katavouta, A., Roussenov, V.M., Foster, G.L., Rohling, E.J. and Williams, R.G. 2018. Pathways to 1.5 °C and 2 °C Warming Based on Observational and Geological Constraints. *Nature Geoscience, 2018 11:2* 11 (2): 102–7. https://doi.org/10.1038/s41561-017-0054-8
12. Wullschleger, S.D., Epstein, H.E., Box, E.O., Euskirchen, E.S., Goswami, S., Iversen, C.M., Kattge, J., Norby, R.J., Van Bodegom, P.M. and Xu, X. 2014. Plant Functional Types in Earth System Models: Past Experiences and Future Directions for Application of Dynamic Vegetation Models in High-Latitude Ecosystems. *Annals of Botany,* 114 (1): 1–16. https://doi.org/10.1093/AOB/MCU077
13. Bechtold, M., G. J. M. De Lannoy, R. D. Koster, R. H. Reichle, S. P. Mahanama, W. Bleuten, M. A. Bourgault, et al. 2019. PEAT-CLSM: A Specific Treatment of Peatland Hydrology in the NASA Catchment Land Surface Model. *Journal of Advances in Modeling Earth Systems,* 11 (7): 2130–62. https://doi.org/10.1029/2018MS001574
14. IPCC. 2021. Climate Change 2021: The Physical Science Basis | Climate Change 2021: The Physical Science Basis.” https://www.ipcc.ch/report/ar6/wg1/
15. Leifeld, J., Wüst-Galley, C. and Page, S. 2019. Intact and Managed Peatland Soils as a Source and Sink of GHGs from 1850 to 2100. *Nature Climate Change 2019 9:12* 9 (12): 945–47. https://doi.org/10.1038/s41558-019-0615-5
16. Humpenöder, F., Karstens, K., Lotze-Campen, H., Leifeld, J., Menichetti, L., Barthelmes, A. and Popp, A. 2020. Peatland Protection and Restoration Are Key for Climate Change Mitigation. *Environmental Research Letters*, 15 (10): 104093. https://doi.org/10.1088/1748-9326/ABAE2A
17. Camill, P., Barry, A., Williams, E., Andreassi, C., Limmer, J. and Solick, D. 2009. Climate-Vegetation-Fire Interactions and Their Impact on Long-Term Carbon Dynamics in a Boreal Peatland Landscape in Northern Manitoba, Canada. *Journal of Geophysical Research: Biogeosciences,* 114 (4). https://doi.org/10.1029/2009JG001071
18. Poulter, B., Christensen, N.L. and Halpin, P.H. 2006. Carbon Emissions from a Temperate Peat Fire and Its Relevance to Interannual Variability of Trace Atmospheric Greenhouse Gases. *Journal of Geophysical Research: Atmospheres,* 111 (D6): 6301, https://doi.org/10.1029/2005JD006455
19. Turetsky, M. R., Donahue, W.F., and Benscoter, B.W. 2011. Experimental Drying Intensifies Burning and Carbon Losses in a Northern Peatland. *Nature Communications,* 2 (1). https://doi.org/10.1038/ncomms1523
20. Wieder, R.K., Scott, K.D., Kamminga, K., Vile, M.A., Vitt, D.H., Bone, T., Xu, B., Benscoter, B.W. and Bhatti, J.S. 2009. Postfire Carbon Balance in Boreal Bogs of Alberta, Canada.

Glob. Change Biol., 15 (1): 63–81. https://doi.org/10.1111/j.1365-2486.2008.01756.x

21. Ingram, R. C., Moore, P. A., Wilkinson, S.L., Petrone, R.M. and Waddington, J.M. 2019. Postfire Soil Carbon Accumulation Does Not Recover Boreal Peatland Combustion Loss in Some Hydrogeological Settings. *Journal of Geophysical Research: Biogeosciences,* 124 (4): 775–88. https://doi.org/10.1029/2018JG004716
22. Davies, G.M., Gray, A., Rein, G. and Legg, C.J. 2013. Peat Consumption and Carbon Loss Due to Smouldering Wildfire in a Temperate Peatland. *Forest Ecology and Management,* 308: 169–77
23. McCarter, C. P.R., Wilkinson, S.L., Moore, P.A. and Waddington, J.M. 2021. Ecohydrological Trade-Offs from Multiple Peatland Disturbances: The Interactive Effects of Drainage, Harvesting, Restoration and Wildfire in a Southern Ontario Bog. *Journal of Hydrology* 601 (October). https://doi.org/10.1016/j.jhydrol.2021.126793
24. Leifeld, J., and Menichetti, L. 2018. The Underappreciated Potential of Peatlands in Global Climate Change Mitigation Strategies. *Nat. Commun.,* 9 (1). https://doi.org/10.1038/s41467-018-03406-6
25. K. Minkkinen, K. A. Byrne and C. Trettin. (In press) Climate impacts of peatland forestry. In, Strack, M. Peatlands and Climate Change, 2nd Edition, International Peatland Society
26. Davidson, S.J., Van Beest, C., Petrone, R. and Strack, M. 2019. Wildfire Overrides Hydrological Controls on Boreal Peatland Methane Emissions. *Biogeosciences,* 16 (13): 2651–60. https://doi.org/10.5194/BG-16-2651-2019.
27. Gray, A., Davies, G.M., Domènech, R., Taylor, E. and Levy, P.E. 2020. “Peatland Wildfire Severity and Post-Fire Gaseous Carbon Fluxes. *Ecosystems,* 24 (3): 713–25. https://doi.org/10.1007/s10021-020-00545-0
28. Morison, M. Q., Petrone, R.M., Wilkinson, S.L., Green, A. and Waddington, J.M. 2020. Ecosystem Scale Evapotranspiration and CO_2 Exchange in Burned and Unburned Peatlands: Implications for the Ecohydrological Resilience of Carbon Stocks to Wildfire. *Ecohydrology,* 13 (2): e2189. https://doi.org/10.1002/ECO.2189
29. Grau-Andrés, R., Davies, G.M., Waldron, S., Scott, E.M. and Gray, A. 2019. Increased Fire Severity Alters Initial Vegetation Regeneration across Calluna-Dominated Ecosystems. *Journal of Environmental Management,* 231: 1004–11. https://doi.org/10.1016/j.jenvman.2018.10.113
30. Hanes, C.C., Wang, X., Jain, P., Parisien, M.A., Little, J.M. and Flannigan, M.D. 2019. Fire-Regime Changes in Canada over the Last Half Century. *Canadian Journal of Forest Research,* 49 (3): 256–69. https://doi.org/10.1139/CJFR-2018-0293/SUPPL_FILE/CJFR-2018-0293SUPPLA.DOCX
31. Jain, P., Castellanos-Acuna, D., Coogan, S.C.P., Abatzoglou, J.T. and Flannigan, M.D. 2021. Observed Increases in Extreme Fire Weather Driven by Atmospheric Humidity and Temperature. *Nature Climate Change, 2021 12:1* 12 (1): 63–70. https://doi.org/10.1038/s41558-021-01224-1
32. Helbig, M., Waddington, J.M., Alekseychik, P., Amiro, B.D., Aurela, M., Barr, A.G., Black, T.A. et al. 2020. Increasing Contribution of Peatlands to Boreal Evapotranspiration in a Warming Climate. *Nature Climate Change,* 10 (6): 555–60. https://doi.org/10.1038/s41558-020-0763-7
33. Hari, V., Rakovec, O., Markonis, Y., Hanel, M. and Kumar, R. 2020. Increased Future

Occurrences of the Exceptional 2018–2019 Central European Drought under Global Warming. *Scientific Reports*, 10 (1): 1–10. https://doi.org/10.1038/s41598-020-68872-9

34. Swindles, G.T., Morris, P.J., Mullan, D.J., Payne, R.J., Roland, T.P., Amesbury, M.J., Lamentowicz, M. et al. 2019. Widespread Drying of European Peatlands in Recent Centuries. *Nature Geoscience, 2019 12:11* 12 (11): 922–28. https://doi.org/10.1038/s41561-019-0462-z
35. Púčik, T., Groenemeijer, P., Rädler, A.T., Tijssen, L., Nikulin, G., Prein, A.F., van Meijgaard, E., Fealy, R., Jacob, D. and Teichmann. C. 2017. Future Changes in European Severe Convection Environments in a Regional Climate Model Ensemble. *Journal of Climate*, 30 (17): 6771–94. https://doi.org/10.1175/JCLI-D-16-0777.1.
36. Mickler, R.A., Welch, D.P. and Bailey, A.D. 2017. Carbon Emissions during Wildland Fire on a North American Temperate Peatland. *Fire Ecology,* 13 (1): 34–57. https://doi.org/10.4996/fireecology.1301034
37. IPCC. 2014. 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands, Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler, T.G. (eds). IPCC, Switzerland. https://www.ipcc.ch/site/assets/uploads/2018/03/Wetlands_Supplement_Entire_Report.pdf
38. Balch, J.K., St. Denis, L.A., Mahood, A.L., Mietkiewicz, N.P., Williams, T.M., McGlinchy, J. and Maxwell C. Cook. 2020. FIRED (Fire Events Delineation): An Open, Flexible Algorithm and Database of US Fire Events Derived from the MODIS Burned Area Product (2001–2019). *Remote Sensing*, Vol. 12, Page 3498 12 (21): 3498. https://doi.org/10.3390/RS12213498
39. Granath, G., Moore, P.A. Lukenbach, M.C. and Waddington, J.W. 2016. Mitigating Wildfire Carbon Loss in Managed Northern Peatlands through Restoration. *Sci. Rep.* 6: 28498. https://doi.org/10.1038/srep28498
40. Crump, J. 2017. Smoke on Water: Countering Global Threats from Peatland Loss and Degradation | GRID-Arendal. https://www.grida.no/publications/355
41. UNEP. 2022. Spreading like Wildfire: The Rising Threat of Extraordinary Landscape Fires | UNEP - UN Environment Programme. https://www.unep.org/resources/report/spreading-wildfire-rising-threat-extraordinary-landscape-fires
42. Harris, L.I., Richardson, K., Bona, K.A., Davidson, S.J., Finkelstein, S.A., Garneau, M., McLaughlin, J. et al. 2021. The Essential Carbon Service Provided by Northern Peatlands. *Frontiers in Ecology and the Environment*. https://doi.org/10.1002/FEE.2437.
43. Nelson, K., Thompson, D., Hopkinson, C., Petrone, R.M. and Chasmer, L. 2021. Peatland-Fire Interactions: A Review of Wildland Fire Feedbacks and Interactions in Canadian Boreal Peatlands. *Science of the Total Environment*., 769: 145212 https://doi.org/10.1016/j.scitotenv.2021.145212.
44. Hein, L., Spadaro, J.V., Ostro, B., Hammer, M., Sumarga, E., Salmayenti, R., Boer, R., Tata, H., Atmoko, D. and Castañeda, J.P., 2022. The health impacts of Indonesian peatland fires. *Environmental Health*, *21*(1), pp.1-16.
45. Ganteaume, A., Camia, A., Jappiot, M., San-Miguel-Ayanz, J., Long-Fournel, M. and Lampin, C. 2013. A Review of the Main Driving Factors of Forest Fire Ignition Over Europe. *Environmental Management*, 51: 651–662 https://doi.org/10.1007/s00267-012-9961-z
46. Wilkinson, S.L., Verkaik, G.J., Moore, P.A. and Waddington, J.M. 2020. Threshold Peat

Burn Severity Breaks Evaporation-Limiting Feedback. *Ecohydrology*, 13 (1). https://doi.org/10.1002/eco.2168

47. Whitman, E., Parisien, M. A., Thompson, D. K., & Flannigan, M. D. 2019. Short-interval wildfire and drought overwhelm boreal forest resilience. *Scientific Reports*, *9*(1), 1-12.
48. Thompson, D.K., Simpson, B.N., Whitman, E., Barber, Q.E., and Parisien M.A. 2019. Peatland Hydrological Dynamics as A Driver of Landscape Connectivity and Fire Activity in the Boreal Plain of Canada. *Forests, 2019, Vol. 10, Page 534* 10 (7): 534. https://doi.org/10.3390/F10070534
49. Kukavskaya, E.A., Soja, A.J., Petkov, A.P., Ponomarev, E.I., Ivanova, G.A., and Conard, S.G. 2013. Fire Emissions Estimates in Siberia: Evaluation of Uncertainties in Area Burned, Land Cover, and Fuel Consumption. *Canadian Journal of Forest Research*, 43 (5): 493–506. https://doi.org/10.1139/CJFR-2012-0367/ASSET/IMAGES/LARGE/CJFR-2012-0367F6.JPEG
50. Evans, C., Artz, R., Moxley, J., Smyth, M.A., Taylor, E., Archer, E., Burden, A., Williamson, J., Donnelly, D., Thomson, A. and Buys, G. 2017. Implementation of an emissions inventory for UK peatlands (pp. 1-88). Centre for Ecology and Hydrology.
51. Mishra, S., Page, S.E. Cobb, A.R. Ser Huay Lee, J., Jovani-Sancho, A.J., Sjögersten, S., Jaya, A., Aswandi, and Wardle, D.A. 2021. Degradation of Southeast Asian Tropical Peatlands and Integrated Strategies for Their Better Management and Restoration. *Journal of Applied Ecology*, 58 (7): 1370–87. https://doi.org/10.1111/1365-2664.13905
52. Strack, M., Davidson, S. J., Hirano, T., & Dunn, C. (2022). The Potential of Peatlands as Nature-Based Climate Solutions. *Current Climate Change Reports*, 1-12.
53. Magnan, G., Sanderson, N.K., Piilo, S., Pratte, S., Väliranta, M., van Bellen, S., Zhang, H. and Garneau, M. 2022. Widespread Recent Ecosystem State Shifts in High-Latitude Peatlands of Northeastern Canada and Implications for Carbon Sequestration. *Global Change Biology,* 28 (5): 1919–34. https://doi.org/10.1111/GCB.16032

Methods

Peatland net ecosystem CO_2 exchange (NEE) was estimated for northern peatlands using literature values for burned, pristine, degraded, and rewetted sites (Table ED1). NEE was estimated over a fire-free interval using values for post-fire (NEE_{burned}) and recovered ($NEE_{recovered}$) periods, where $NEE_{recovered}$ could represent one of undrained, drained, or rewetted NEE. Annual values of NEE were derived using a simple conceptual model of NEE recovery from its post-fire to recovered state (Figure ED1). The recovery of NEE was represented by a piecewise linear function with two input parameters (t_1 and t_2) which define the time period (time since fire; TSF) over which NEE transitions from its post-fire to recovered state (Eq. 1). NEE values were collated from plot-scale measurements alone due to the limited number of ecosystem-scale (i.e., eddy covariance) measurements for both drained and recently burned northern peatlands. Using the dataset from Webster et al.[53] for Canadian peatlands, we filtered their data for plot-scale measurements. We supplemented the data set with additional NEE data from the northern hemisphere, including plot-level data from drained, restored, and recently burned peatlands (Table S1). In order to ensure consistency, we calculated NEE according to the methods outlined by Webster et al.[53] . For simplicity, methane fluxes were assumed to not vary systematically over the fire free interval, where again we supplemented the Webster et al.[53] data set with CH_4 flux data from drained and burned sites. Annual values of NEE and CH_4 fluxes were converted to g C and summed to get the net ecosystem carbon balance (NECB), where fluvial exports were not considered. From the data set, we derived four distributions of NECB: (i) burned; (ii) undrained; (iii) drained; and (iv) restored. A Monte Carlo simulation was used to combine sources of uncertainty and generate an annual average NECB estimate for non-permafrost northern peatlands which included carbon emissions from wildfire. Two separate distributions of carbon emissions from wildfire were used for drained and undrained sites. No peatland eddy covariance flux monitoring has occurred which directly quantifies the recovery rate of NEE post-fire. However, chronosequence chamber measurement data (e.g., Wieder et al. [20]) shows that recovery of NEE to a pre-fire state corresponds with vegetation recovery.

$$NEE = \begin{cases} NEE_{burned} & TSF < t_1 \\ NEE_{burned} + (NEE_{recovered} - NEE_{burned})\dfrac{TSF - t_1}{t_2 - t_1} & t_1 \leq TSF \leq t_2 \\ NEE_{recovered} & TSF > t_2 \end{cases}$$

Equation 1. Net ecosystem exchange calculation used in Monte Carlo modelling simulations.

Fire-free interval was calculated for non-permafrost boreal and temperate biomes using fire polygon data from FIRED[38] (Figure S1). Fire polygon data covers the period of November 2001 to July 2021, providing 19.75 years of data with consistent methodology used across the time series and all spatial regions (Table S2). Ecoregion polygons from the World Wildlife Fund Terrestrial Ecoregions of the World[54] were used to obtain boreal and temperate biome polygons by joining ecoregion polygons based on biome attribute. These biome polygons were clipped to remove permafrost regions using a permafrost extent layer[55]. Where discontinuous, and continuous areas of permafrost were considered permafrost in our study. Data were then further separated by continent (Europe, Asia, North America) to identify continental and biome differences in area burned. Area burned over the 19.75 year period was calculated by summing the total area attribute (tot_ar_km2) from the FIRED data set which was contained within each biome × continent. The total area burned was then divided by 19.75 (years of data) and the land area of each biome × continent to produce a burn rate (% land yr^{-1}) which was then converted to fire free interval (Table ED2). All analyses were conducted using QGIS 3.6[56].

The distribution of calculated fire free intervals was in-line with fire free intervals (also called fire return intervals) recorded in the literature for boreal and temperate peatlands (Table S3) using a variety of methods (e.g., macroscopic charcoal analysis, tree ring fire scars, GIS analyses). However, we do note the bias towards studies conducted in Canada, likely due to the dominance of anthropogenic ignitions (and therefore erratic nature) of wildfires in European peatlands. Further, given the relative sparsity of data on peatland wildfire frequencies, as well as the variation in peatland mapping accuracy and resolution across the broad study area and the conversion of peatlands to alternate landcover types (e.g., forest, agriculture[25]), we assume that peatland burn rate (peatland area burned yr^{-1}) is equal to the calculated burn rate (% land yr^{-1}). This is supported by research that found that peatlands in boreal Canada burn at their expected rate, based on landscape cover[57,58], and that ignitions don't vary based on landscape type. Moreover, methodologies that utilise macroscopic charcoal layers to determine fire free interval are likely to underestimate fire frequency due to the potential erasure of charcoal layers in higher severity fires[21] and the possible loss or relocation of charcoal from a given peatland location before it is incorporated into the peat matrix[57], all biasing towards longer estimates of fire free intervals than actually occur.

We assessed the interactive effect of fire regime changes (peatland area burned; % yr^{-1} and peat carbon loss; kg C m^{-2}) and land use change (percent of peatland area that is degraded; %) on peatland NECB (Gt C yr^{-1}) by varying two of the three parameters concurrently within realistic bounds. While two parameters were varied between their lower and upper limits, the third parameter was held (relatively) constant. In the case of varying peatland area burned and peat combustion carbon loss (Figure 2b), the third parameter, percent degraded, was held constant at 7 % given that there is no distribution associated with this parameter. Similarly, peatland area burned was held constant at 0.5 %. Whereas, peat carbon loss was allowed to vary within its observed distribution from the data synthesis (Table ED1). Repeated simulations were run using a Monte Carlo framework where fire return interval, recovered and initial sink strength, and recovery time were varied as described in Table ED1. The black filled dots represent the current northern non-permafrost peatland system in the NECB phase space.

To evaluate the global importance of peatland emissions we calculated the cumulative median NECB value from the Monte Carlo simulations over the current century for simplified scenarios of pristine (100 %), degraded (100 %), and rewetted (100 %) peatlands for all northern non-permafrost peatland area. The timeseries of RCB are based on low emissions scenario (RCP2.6) and moderate emissions scenario (RCP4.5), for two remaining carbon budgets of 440 Gt CO_2 and 1,190 Gt CO_2 starting at 2020 based on targets for limiting average global temperature rise to 1.5°C and 2.0°C, respectively, over the 21st century.

Data Availability Statement

Synthesized data will be uploaded to a certified repository and model simulations code are available upon request to the authors. Supplementary Information is available for this paper.

References (Methods)

53. Webster K.L., Bhatti, J.S., Thompson, D.K., Nelson, S.A., Shaw, C.H., Bona, K.A., Hayne, S.L. and Kurz, W.A. 2018. Spatially-integrated estimates of net ecosystem exchange and

methane fluxes from Canadian peatlands. *Carbon Balance Manage*., 1311–21

54. Olson, D.M., Dinerstein, E., Wikramanayake, E.D., Burgess, N.D., Powell, G.V.N., Underwood, E.C., D'Amico, J.A., Strand, H.E., Morrison, J.C., Loucks, C.J., Allnutt, T.F., Lamoreux, J.F., Ricketts, T.H., Itoua, I., Wettengel, W.W., Kura, Y., Hedao, P. and Kassem, K. 2001. Terrestrial ecoregions of the world: A new map of life on Earth. *BioScience*, 51(11):933-938
55. Gauthier, S., Bernier, P., Kuuluvainen, T., Shvidenko, A. Z., and Schepaschenko, D. G. 2015. Boreal forest health and global change. *Science*, *349*(6250), 819-822.
56. QGIS Development Team. 2019. QGIS Geographic Information System – Version 3.6. Open-Source Geospatial Foundation Project. http://qgis.osgeo.org
57. Turetsky, M. R., Amiro, B.D., Bosch, E. and Bhatii, J.S. 2004. Historical burn area in western Canadian peatlands and its relationship to fire weather indices. *Global Biogeochemical Cycles*, 18(4): https://doi.org/10.1029/2004GB002222
58. Marchal, J., Cumming, S. G., & McIntire, E. J. 2017. Exploiting Poisson additivity to predict fire frequency from maps of fire weather and land cover in boreal forests of Québec, Canada. *Ecography*, *40*(1), 200-209. https://doi.org/10.1111/ecog.01849

Extended Data

Table ED1. Input parameters derived from data synthesis used in Monte Carlo simulations for calculation of peatland net ecosystem carbon balance.

Input	State	Distribution	Parameter 1	Parameter 2
NEE (g C m^{-2} yr^{-1})	burned	Normal	Mean = 142	SE = 38.0
	degraded	Normal	Mean = 172	SE = 17.2
	rewetted	Normal	Mean = -8.0	SE = 20.2
	pristine	Normal	Mean = -59.5	SE = 10.2
Fire C-loss (kg C)	degraded	uniform	Min. = 2.3	Max. = 16.8
	pristine	log-normal	Mean = 0.587	SD = 0.907
Fire free interval	–	uniform	40	350
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.

Region	**Biome**	**Total area (10^6 km^2)**	**Burned area (10^6 km^2)**	**Fire free interval (years)**	**Burn rate (% yr^{-1})**
Asia	Boreal	3.01	0.392	154	0.649
	Temperate	–	–	N/A	
Europe	Boreal	2.35	0.025	1870	0.054
	Temperate	4.44	0.889	100	1.00
North America	Boreal	3.45	0.261	264	0.379
	Temperate	2.83	0.085	620	0.161

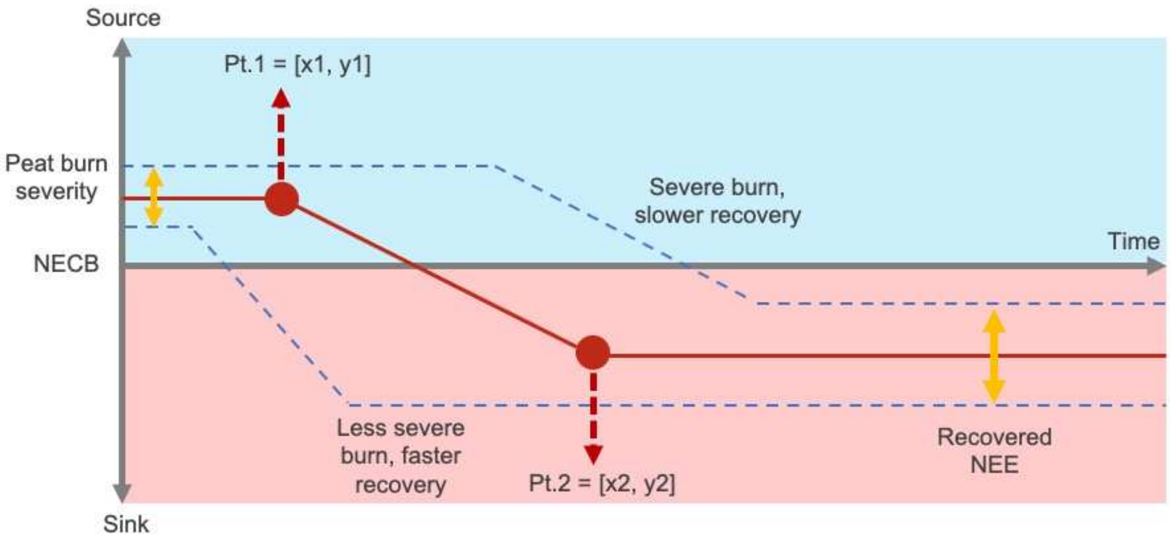

Figure ED1. Conceptual diagram of the modelling design developed to incorporate peat carbon loss from wildfire (peat burn severity) and post-fire carbon dynamics (recovery rate and recovered net ecosystem exchange (NEE)) on net ecosystem carbon balance (NECB). Where Pt. 1 represents the time lag between wildfire and the initiation of post-fire recovery and Pt. 2 represents the time at which “recovered” NEE is achieved and 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 dash lines.

Supplementary Files

- WilkinsonetalSupplementaryMaterial20220729.pdf