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Peat fires and the unknown risk of legacy metal and metalloid pollution

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1. Introduction

Peatlands have persisted for millennia, acting as globally-important sinks of atmospheric carbon dioxide (Yu 2012) and regionally-important role sinks of pollutants, such as lead, arsenic, or mercury (toxic metals and metalloids, TMMs) (Bindler 2006). The role peatlands play in atmospheric carbon sequestration often overshadows their role in storing pollutants despite, for example, peat mercury accumulation rates increasing 60–130× relative to pre-industrial rates (Bindler 2006). Peatlands sustain their carbon and TMM sink persistence through a suite of ecohydrological feedbacks and plant traits (Souter and Watmough 2016, McCarter *et al* 2020). However, the interaction of climate change, land-use change and wildfire are testing peatland resilience (Wilkinson *et al* 2023), potentially placing their long-term stores of recent and legacy carbon and TMMs on the edge of catastrophic release.

Smoldering peat fires can emit at least two orders of magnitude more particulate matter and carbon than flaming fires, having important implications for the global carbon cycle (Turetsky *et al* 2015). Peat fires also release TMMs through particulate emissions (Betha *et al* 2013) and surface water runoff (Paul *et al* 2022), both of which can have detrimental impacts on regional human health (Finlay *et al* 2012). For example, particulate smoke emissions from the 1997/98 Indonesian peat fires caused immediate and delayed effects on human mortality, with over 35 000 excess deaths per year in south-east Asia due in part to TMM-containing particulates emitted from smoldering peat fires (Betha *et al* 2013). Globally, peatland wildfires have been estimated to significantly increase global mercury emissions in severe fire years by over two orders of magnitude, where mercury emissions in those years can be over 150 and 800 Mg yr^{-1} in the boreal and south-east Asia regions, respectively (Friedli *et al* 2009), from what was considered a long-term mercury sink.

Wildfire mobilization of TMMs is especially concerning in industry-impacted landscapes, where TMMs in surface peat (the most likely to burn) can be elevated well above (10s–100s times higher) natural concentrations (Shuttleworth *et al* 2017). Lead and copper concentrations can exceed 1600 mg kg^{-1} in industrially contaminated peatlands (Souter and Watmough 2016, Shuttleworth *et al* 2017), which equates to potential peat fire emissions/mobilization of ∼0.32 Mg ha^{-1} each from the upper 10 cm of the peat profile. In contrast, potential lead emissions/mobilization (5–21 Gg yr^{-1}) from the same depth of burn in undisturbed northern hemisphere peatlands (∼0.004–0.016 Mg ha^{-1}) (Bindler 2006, Souter and Watmough 2016) would be comparable to emissions from several industrial sectors (Rauch and Pacyna 2009), assuming a 0.35% burn area (Wilkinson *et al* 2023), 3.7 million km^2 of peatlands (Yu 2012), and all lead is emitted/mobilized. While emissions of TMMs with low volatilization temperatures, such as Hg, have been quantified, the high smoke particulate concentration from low temperature smoldering peat fires often contain high TMM concentrations but emission factors for TMMs have not been extensively determined, limiting our ability to accurately quantify this risk.

Given that future warmer and drier conditions, as a direct consequence of climate change, are expected to increase fire frequency, burn severity, and area burned (Hanes *et al* 2019), the danger of peat fires mobilizing and releasing recent and legacy TMMs is likely increasing. The level of risk associated with TMM release is, however, unknown. Therefore, there is an urgency to better understand and predict peat fire TMM release and to mitigate this release through adaptive management and restoration strategies. Here we identify current known-unknowns (1–3) and mitigation measures (4) to address this emerging environmental disaster.

1. Unknown Geographies of Legacy Peatland Pollution
2. Unknown Impact of Climate Change on Peatlands
3. Unknown Interactive Processes with Peat Fires
4. Mitigating Peatland TMM Legacies.

2. Known-unknown #1: unknown geographies of legacy peatland pollution

Peatlands have been recording industrial pollution for centuries, with TMM pollution, mostly lead, dating back to the Roman Period in Europe (Bindler 2006). Depending on the local atmospheric conditions and residence time of the TMM, many TMMs are deposited near (hundreds of km) the emission source but certain atmospheric pollutants, such as mercury, can be deposited 1000s of km from the emission source (Rahman and Singh 2019). Thus, the duration of emissions combined with the specific atmospheric residence time will ultimately control TMM deposition to receiving peatlands, where longer emission duration and shorter atmospheric residence times often produce the most intense peatland contamination (Bindler 2006, Rahman and Singh 2019). However, the long history of TMM deposition and lack of accurate deposition maps for much of human history creates significant uncertainty on where potential legacy peatland TMM stores are located.

Peat that has accumulated in peatlands since TMM deposition peaked and/or ceased has made the location of the TMM stores within the peat profile uncertain, further complicating spatial uncertainties in legacy TMM stores. Peatlands with considerable peat accumulation following TMM deposition may have legacy TMMs stored at depth (figure 1(A)), resulting in a potential uncontaminated buffer between the burning surface peat and legacy pollution. In contrast, peatlands with recent TMM deposition and/or limited recent peat accumulation would be more likely to release that pollution load from the contaminated peat during fires (figure 1(E)). Coupling the spatial uncertainties in TMM deposition with the uncertainty in the distribution of TMMs in the peat profile represents an unknown risk to human and environmental health. To properly assess this risk from peatland fires, there is an urgent need to know the spatial extent of polluted peatlands, what TMMs are stored within them, and how deep the pollutants are located within the peat profile. The urgency is enhanced by the intensifying role of climate change in fire occurrence and severity (Hanes *et al* 2019).

3. Known-unknown #2: unknown impact of climate change on peatlands

The rate of future peat and peat-carbon accumulation in response to the interactions of peatland types (e.g. bog, fen, swamp) and climate change remains highly uncertain (Page and Baird 2016). While projected drying due to climate change is expected to decrease carbon accumulation rates (Helbig *et al* 2020), the magnitude of change is unknown due to variations in peatland type and internal microtopographic resilience to drying (Page and Baird 2016). This uncertainty is driven by the specific interactions between biogeochemical processes, such as peat decomposition, and the organic peat structure (peat properties) that are unique to different peatland types and peat surface microtopographies (McCarter *et al* 2020). As such, the future 'strength' of the aforementioned recent surficial peat buffer is highly uncertain (figures 1(B)–(D)). Near-surface peat properties provide a strong control on peat fire combustion (measured as depth of burn) through the interaction of peat density and moisture content (Wilkinson *et al* 2019). While wet peat rarely burns, peatland drying by climate change or drainage increases the likelihood of ignition and depth of burn from several centimeters to decimeters (Wilkinson *et al* 2019) (figure 1—yellow lines). Predicting the change in depth of burn due to climate change is, however, highly uncertain due to variability in fuel load, peat properties, and groundwater connectivity that drives peatland type (Wilkinson *et al* 2019).

Further complicating the relationship between climate change and peatland fires are interactions with land-use change. Globally, over 25% of peatlands have been drained, mainly for agriculture and forestry, with deeper water table levels switching peatlands from atmospheric carbon sinks to sources (Page and Baird 2016). Combustion of drained peatlands increases greatly, with some depth of burn observations exceeding 1 m (Wilkinson *et al* 2023). As such, the likelihood that depth of burn reaches and releases a greater proportion of legacy TMM stores, regardless of peat buffer accumulation, increases with both peatland drainage and climate change (figure 1—red lines). While peatlands can absorb low rates of TMM deposition, even over long time periods (Bindler 2006), at some unknown threshold the combined

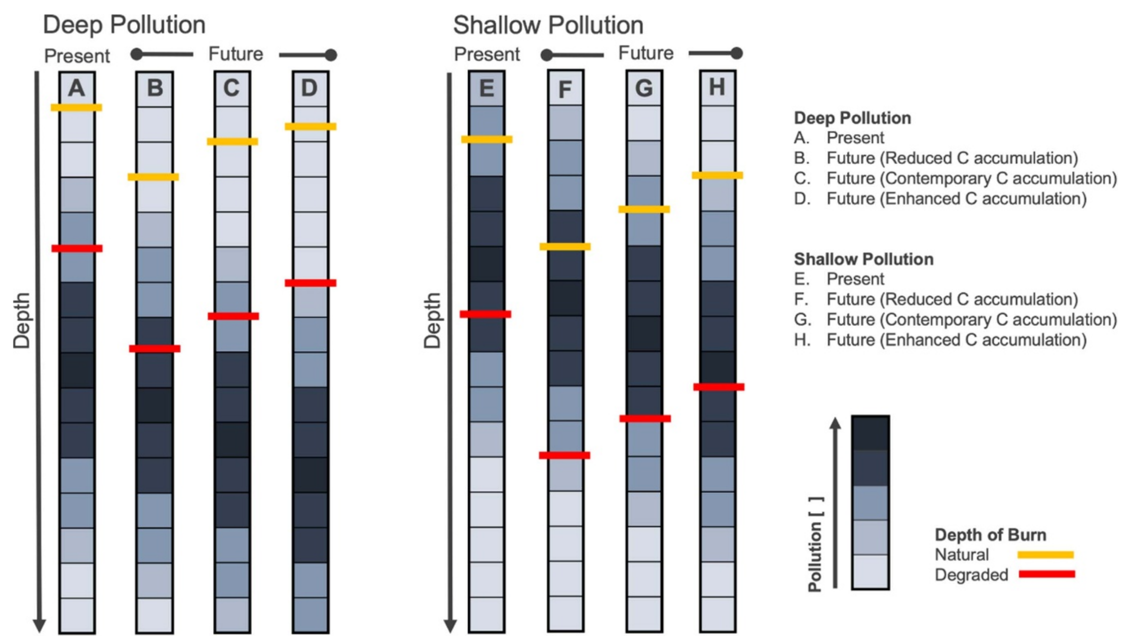

Figure 1. Conceptual diagram illustrating hypothetical present and future deep (Left) and shallow (Right) TMM pollution scenarios under future reduced, contemporary, and enhanced carbon accumulation rates. Contemporary and climate change enhanced future depth of burn are shown for natural (yellow lines) and degraded (red lines) peatlands, respectively.

TMM load overwhelms the natural ecohydrological feedbacks (McCarter *et al* 2020), degrading peatland functionality and reducing wildfire resistance. Thus, the overall likelihood of TMM release will be a function of not only the peatland type, and past and current disturbances including climate change, but also the intensity of legacy and current TMM deposition history (figure 1).

We suggest the breadth of peatland types severely limits our ability to identify which peatlands are most vulnerable to climate change enhanced fire occurrence. As such, there is a clear research need to develop peatland models (numerical and conceptual) that consider the interaction of ecohydrological feedbacks, carbon cycling and smoldering combustion dynamics to better establish the physical factors that drive peat flammability under a changing climate. This information is critical to developing mathematical models of peat burn severity that consider peatland degradation status, peatland type and landscape position. Ideally, this model would be combined with mapping of peatland pollution loadings to identify current peatlands at greatest risk of the release of legacy TMM pollution and future risks under a drying and warming climate.

4. Known-unknown #3: unknown interactive processes with peat fires

Peatlands rely on a delicate balance of interacting hydrological, biological, and geochemical processes to persistently sequester recent and legacy TMM pollution. Disruption of any one of these processes can result in a release of previously sequestered TMMs. Fire is a transformative force in many ecosystems that changes hydrology, biology, and geochemistry. Peatlands are no exception, but how these underlying processes change due to fire and subsequently interact to alter TMM mobility is poorly understood. Toxic metal and metalloid mobility within and out of peatlands is governed by biogeochemical and hydrophysical processes, increasing with, for example, increasing organic matter aromaticity (Caporale and Violante 2016) and erosion (Shuttleworth *et al* 2017), as well as shifts in pH (Caporale and Violante 2016). However, for mobilized TMMs to reach aquatic ecosystems, there needs to be active hydrological flow paths to effectively convey the TMMs (i.e. ecohydrological connectivity) that can be modified by fires in the peatland and the surrounding landscapes. However, such changes to ecohydrological connectivity do not always correspond to the fire season, temporally disconnecting water quality impacts from the peatland fires (Olefeldt *et al* 2013). Atmospheric deposition of TMMs contained within ash can provide an alternative and direct vector for TMM mobility during and after a fire (Finlay *et al* 2012) but we currently lack specific emission factors of the wide range of TMM chemistries and peat types needed to quantify this pathway. Thus, TMM mobility and toxicity are potentially impacted by fire-induced changes in ecohydrological connectivity, biogeochemistry and geomorphology, as well as direct ash-derived deposition, making the ultimate magnitude and fate of TMM pollution uncertain.

Our understanding regarding the mechanisms and pathways of TMM mobilization due to peat fires remains limited. A key step to mitigating peat fire risks is to develop an international consensus on the processes and feedbacks between fire, hydrology, climate, biogeochemistry and ecology that influence TMM mobility before, during, and after fire. We argue for the formation of an international peat fire monitoring network to tackle these unknown interactive processes and encourage more hydrologists, ecologists, wildfire scientists and biogeochemists to bring their expertise from other disciplines to the peat fire research community.

5. Mitigating peatland toxic metal and metalloids legacies

These three known-unknowns are clear barriers to predicting, minimizing and mitigating the risk to human and environmental health from peat fire TMM release. Additionally, some contaminated peatlands will require intervention to prevent the release of TMMs, but restoring and/or rewetting TMM contaminated peatlands will likely require alternative and untested techniques (McCarter *et al* 2023). Because ecosystem restoration can take decades to accumulate buffer peat of sufficient thickness to reduce burn severity, we suggest that it is imperative to consider if the relative rates of restoration can buffer against climate change enhanced burning or if other (currently) unknown contamination remediations are needed to artificially decrease the likelihood of peat ignition. Despite reductions of point source TMM emissions and the potential to mitigate this impending disaster through yet untested and unknown approaches, we argue there is an urgent enough need to focus policy and research into halting and reversing peatland degradation that also minimizes future risks for environmental and human health exposure to the toxic environmental legacy held within global peatlands.

Data availability statement

No new data were created or analyzed in this study.

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Author contributions

C P R M and J M W conceptualized, wrote, and edited the paper and conceptualized, designed, and created the figures. S P, G D C and E L S conceptualized and edited the paper. All other authors edited the paper.

Conflict of interest

The authors declare no competing interests.

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