



Ideas and Perspectives: Potentially Large but Highly Uncertain Greenhouse Gas Emissions Resulting from Peat Erosion

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Abstract

Peatland erosion and resulting particulate organic carbon (POC) flux is an international problem that is causing loss of peat
15 carbon to the atmosphere and contributing to climate change. Peatlands from around the world are eroding and losing carbon
for a range of reasons, from overgrazing to climate change, and the POC is subsequently exposed to a diverse range of
conditions, depending on the geographical context. The context, drivers of erosion and downstream environment will directly
influence the rate at which POC is mineralised to CO₂ by microbial communities. Despite the potential large carbon losses
from POC and subsequent CO₂ emissions the mechanisms for emissions reporting at international and national level are
20 undeveloped. Here we highlight the key limitations for understanding and quantifying emissions that result from peat erosion
and discuss the research that is required to address these limitations. We particularly consider quantification of direct CO₂
emissions from bare peat and resedimentation and further turnover at different scales. By integrating biological and
geomorphological process understanding we can work towards better quantification of peatland emissions and the emissions
that can be avoided through peatland ecosystem restoration.

25 1 Peatland Erosion and Potential Emissions

Peatlands have been under severe threat from various anthropogenic factors such as pollution, drainage and intensive utilisation
for food and fibre production and many are now strong net sources of carbon to the atmosphere. Exposure of bare peat,
exacerbating erosion and sediment transport downstream, is a pressing problem because it causes a loss of carbon to the
atmosphere and reductions in water quality (Evans and Warburton, 2011). This issue is particularly prevalent in the UK and
30 Ireland where erosion gullies form on sloping upland blanket bogs and are subject to strong wind, rainfall, fluctuations in
temperature and moisture, with bare and eroding peatlands being commonplace (Li et al., 2018b). A large body of research

has examined the geomorphological controls on peat erosion, especially from the perspective of sediment load (Reviewed in Li et al. (2018b)). However, as governments and landowners look to quantify and reduce greenhouse gas (GHG) emissions from peatlands, focus should turn to quantifying those that result from peatland erosion.

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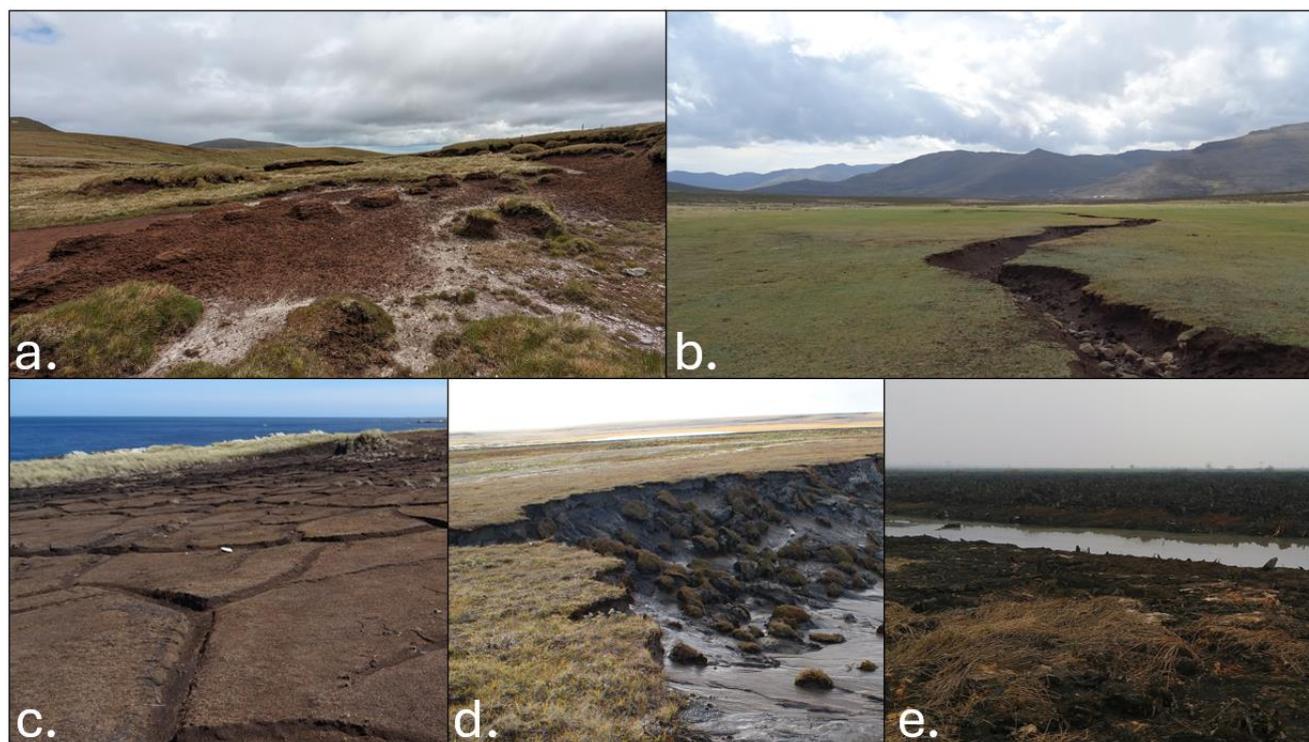
Climate change can potentially enhance rates of erosion through more extreme weather events (e.g. Cotterill et al. (2021)). For example, drought can cause desiccation of the peat, and impact by heavy rain can cause ‘wind splash’ impacts and rapid overland flow, contributing to destabilisation and transport of the peat (Warburton, 2003). In contrast, reduced frost days and fewer freeze-thaw cycles could reduce erosion caused by needle ice (Li et al., 2018a). Interactions between climate change and erosion are complex and often ecosystem/biome or region specific. Nonetheless, erosion of peat is projected to change in the coming century with sediment yields projected in different regions decreasing or increasing by -1.27 to $+21.63$ $\text{t ha}^{-1} \text{yr}^{-1}$ by 2800 (Li et al., 2017). It is therefore important to understand the links and feedbacks between climate, land use, peat erosion and GHG emissions.

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45 Peat erosion is a pressing problem for peatland systems beyond the UK (where historical research effort has been focussed), with potential for massive carbon losses and climate feedbacks (Fig.1). For example, collapse of inland permafrost systems in the arctic and boreal regions (Swindles et al., 2015) can cause localised rapid erosion and movement of soil carbon via thaw slumps (Lamoureux et al., 2014; Pizano et al., 2014), with potential for high emissions as the mobilised carbon becomes available to decomposer organisms. Equally, arctic permafrost coastal erosion and coastal-adjacent thaw slumps are occurring at an alarming rate in response to rapid warming around the Arctic Ocean (Lantuit and Pollard, 2008; Lantuit et al., 2012). In the tropics of Southeast Asia, coastal erosion of peatlands is causing large direct fluxes of peat to the ocean (Kagawa et al., 2024), and in the islands of the South Atlantic, wind erosion to the ocean is a strong driver of peat C loss (Selkirk and Saffigna, 1999; Wilson et al., 1993). At the level of IPCC national emissions reporting there is the acknowledgement that that particulate organic carbon (POC) could be the ‘dominant form of soil carbon loss’ from eroding peatlands (Ipcc, 2014). However, emissions calculations via this route are based on data gathered from the UK only, based on POC export rates, the proportion of a peatland that is bare and a POC-CO₂ conversion rate of 70%. Depending on the context, biome and global location, estimated emissions resulting from peat erosion could vary significantly from currently reported rates.

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60 **Figure 1: Bare peat in a. Scotland (Photo T. Parker), b. Lesotho (Photo C. Evans), c. Falkland Islands (Photo C. Evans), d. Siberia (©ESA; Photo Annett Bartsch) and e. Indonesia (Photo S. Smith).**

The national GHG inventory in the UK attributes $5.44 \text{ t CO}_2\text{e ha}^{-1} \text{ yr}^{-1}$ to direct emissions from bare peat and $10.27 \text{ t CO}_2\text{e ha}^{-1} \text{ yr}^{-1}$ from CO_2 evolving from POC downstream of the erosion locations (Evans et al., 2022). Mapping of bare peat extent at high resolution is progressing (Macfarlane et al., 2024) but the underpinning data for estimating emissions associated with bare peat are highly uncertain (Evans et al., 2013) as the flux depends on specific fluvial mixing events in time and space (Palmer et al., 2016). Eroded peat will potentially be processed and mineralised in multiple environments, from headwater streams, floodplains to rivers and the ocean (Evans et al., 2013; Zhou et al., 2021). Therefore, key research questions and context dependencies need to be addressed before we can confidently attribute emissions to peat erosion. Here, we highlight two research questions that can help bridge the gap between measuring peat erosion and attributing GHG emissions factors:

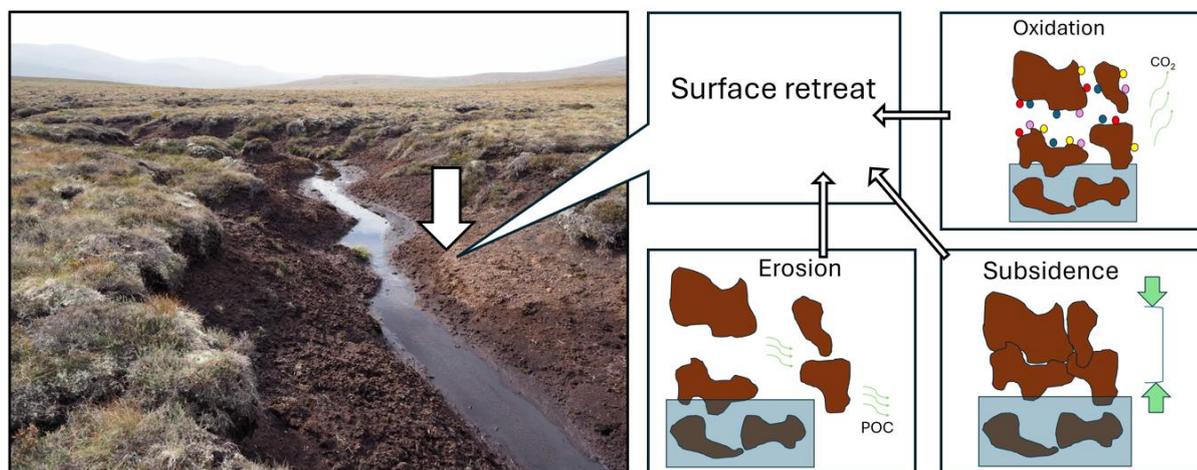
- When peat is exposed to the atmosphere, how much carbon is lost as CO_2 compared to other mechanisms of peat volume loss?
- When peat erodes, how much is resedimented, oxidised or continues to be transported out of the erosion complex?



75 **2 When peat is exposed to the atmosphere, how much carbon is lost as CO₂ compared to other mechanisms of peat volume loss?**

2.1 Erosion

Peat sediment can be destabilised by needle-ice production, wind-splash and desiccation and then transported offsite by rill and interrill water erosion and wind erosion. Bare peat in gullies or flats is under significant erosion pressure from these
80 processes (Li et al. (2018b); Evans and Warburton (2008)). For the purposes of this article we do not consider wind erosion because although lateral transport may be significant (0.46-0.48 t sediment ha⁻¹ yr⁻¹ (Warburton, 2003)), in the absence of more information we assume the wind-eroded peat is retained within the erosion system. This is likely true in winter when wind-splash may move the sediment a matter of cm (Warburton, 2003), and can be integrated into water erosion, however this
85 is likely untrue for summer when peat desiccation occurs and small peat particles could be subject to longer-range aeolian transport or in farmed fens that maybe extensively ploughed (Cumming, 2018). This is one of the many uncertainties and context dependencies that needs to be addressed to better partition fluxes of CO₂ against other apparent losses of peat from eroded systems (Fig.2).



90 **Figure 2: Erosion gully with visible drying of the bare peat and rill erosion/water flow carrying POC downstream, vertical arrow indicates direction of peat surface change. Right- potential co-occurring forces that result in measurable surface retreat of bare peat.**

2.2 Respiration and loss to CO₂

Peat is formed from partially-degraded remains of plant material that have remained *in situ* from centuries to millennia, as a result of a shallow water table. Once this relatively undegraded material (Biester et al., 2014) is released from hydrological
95 controls on its decomposition -i.e. it is exposed to an abundance of oxygen, new microbial communities and warmer temperatures- it has potential to rapidly degrade (Artz et al., 2008; Robinson et al., 2023). Coupled with an absence of primary productivity on the unvegetated peat, exposure of peat to aerobic conditions can lead to a sizable CO₂ flux (but a reduced CH₄ flux compared to vegetated bog) (Artz et al., 2022; Evans et al., 2021b). The CO₂ flux from bare peat is termed “wastage”



(Evans et al., 2006) and is difficult to measure from eroding peat surfaces because they are highly dynamic and remote, therefore wastage is often quantified through process of elimination after independently-measured fluxes of wind and water erosion are subtracted from measured peat loss (Evans et al., 2006; Francis, 1990). Francis (1990) observed greatest surface retreat rates (SRR) of bare peat in the summer when peat temperatures were highest, despite the highest flux of eroded sediment in the winter, leading to the conclusion that direct CO₂ flux from the bare peat was a major loss pathway. Among the few papers that have estimated peat wastage, there is large uncertainty as to the importance of this process, with estimates ranging from around 56-81% of the measured SRR (Francis, 1990), to 5.75% measured directly through mass loss (Pawson, 2008). Evans et al. (2006) estimated wastage rates between 30-46 % depending on site characteristics (calculated by subtraction (Evans et al., 2006)). Chamber based GHG flux measurements estimate bare peat in gullies to be a small summer source of CO₂, although the literature is sparse with very few year-round measurements and/or modelling studies to estimate annual budgets (Dixon et al., 2014; Clay et al., 2012; Gatis et al., 2019). However, at one blanket bog site, ecosystem respiration in vegetated gullies was found to be the highest within the landscape (Mcnamara et al., 2008), reinforcing how variable this flux could be.

2.3 Subsidence

Erosion gullies cause drainage of the bare and surrounding vegetated peat (Daniels et al., 2008). Low water-table depths can cause subsidence of peat through reduction of water in peat soil pore spaces and the associated reduction of buoyancy. As a result, pore spaces collapse, the density of peat increases, and the peat loses elevation. This phenomenon is well understood in peatlands where drainage is implemented for plantations in the tropics (Hooijer et al., 2012), agriculture in temperate systems (Hutchinson, 1980) or on forested or drained temperate-boreal bogs (Defrenne et al., 2023; Sloan et al., 2019; Williamson et al., 2017). When drainage is imposed on bogs they can subside at a range of rates, from 0.5m over 100 years (Defrenne et al., 2023) to 2m in 20 years (Hooijer et al., 2012). In the Flow Country of Scotland, drainage for forestry caused a 57 cm average subsidence on a blanket bog over 50 years (Sloan et al., 2019), which could have been caused but a combination of heavy machinery (required for forestry) and the biotic drivers of peat carbon loss caused by trees (Defrenne et al., 2023) in addition to subsidence. Bare peat within eroding blanket bogs have SRR that are double (see next section and Li et al. (2018b)) the rate of elevational change attributed to subsidence in drained, forested systems (Sloan et al., 2019), and this elevation change occurs in the absence of factors associated with forestry. Nonetheless, subsidence of peat could be an important factor for apparent surface retreat from eroding peatland systems, and by not accounting for it we may overestimate carbon losses as direct CO₂ or POC into the fluvial system.

To try to account for this potential covariation with CO₂ loss, subsidence and POC losses it could be informative to compare SRR at multiple points within a peatland system. After drainage, subsidence and CO₂ loss could be a considered a smooth linear or nonlinear process (Hooijer et al., 2012), consistently measurable across relatively large areas of drained land.



Therefore, if subsidence was the driving factor behind bare peat SRR one would expect an even SRR across all spatially distributed observation points (depending on topography and drainage). In reality, SRR is stochastic and spatially variable within very small areas ($< 1 \text{ m}^2$). Eroding blanket bogs are often on slopes and therefore subject to strong lateral surface flow of water (Evans and Warburton, 2008). Therefore, it is likely that water erosion is the primary cause of SRR in blanket bog systems. Methods for measuring peatland subsidence at high resolution are now available at low cost (Evans et al., 2021a), hence the relative role of subsidence of the whole peat system could be compared with loss rates at specific points on the bare peat, as traditionally measured by erosion pins. These scalable metrics for peat erosion/wasting and subsidence should be prioritised to help better estimate direct CO_2 emissions from bare peat. The drivers of SRR potentially include direct oxidation by microbial communities in aerobic conditions, subsidence resulting from reduced peat buoyancy and erosion (Fig. 2), the relative proportions of which will influence how much GHG emission can be attributed to SRR.

2.4 Estimating CO_2 Emissions from Bare Peat

To evaluate potential peat wastage rates from bare peat surfaces, we assumed no subsidence (while acknowledging this may cause overestimates of other losses) and applied emissions factors to data compiled by Li et al. (2018b). We calculated a median SRR of 18.9 mm yr^{-1} for UK eroding blanket bogs from 22 datasets that contributed to the review by Li et al. (2018b) (Table 1). We then applied a best estimate of 35 % wastage rate (Evans et al., 2006), although this could vary between 5% (Pawson, 2008) and 80% (Francis, 1990), and UK average peat bulk density and carbon content (extracted from UK soil Database (Frogbrook et al., 2009)) to estimate carbon loss from bare peat surfaces of $16.7 \text{ tCO}_2\text{e ha}^{-1} \text{ yr}^{-1}$. Taking a UK average of 15 % bare peat for eroding blanket bogs and combining average emissions for vegetated ‘modified bog’ (Evans et al., 2017) of $2.51 \text{ tCO}_2\text{e ha}^{-1} \text{ yr}^{-1}$ estimates direct GHG fluxes from eroding blanket bogs to be $4.6 \text{ tCO}_2\text{e ha}^{-1} \text{ yr}^{-1}$. This represents a potentially large flux of carbon from peat bogs to the atmosphere. Although these calculations are based on very limited data, this rough estimate is comparable to a recently published paper where authors measured net ecosystem exchange of $3.6 \text{ tCO}_2\text{e ha}^{-1} \text{ yr}^{-1}$ over an eroding blanket bog with approximately 15 % bare peat cover (Artz et al., 2022). Similarly, a former peat extraction site in Quebec with low vegetation coverage represented a large carbon source of between 5.8 and $8.7 \text{ t CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$ (Rankin et al., 2018), indicating that bare peat could be a large source of CO_2 .

To our knowledge, only a single study has measured oxidation of bare peat, via mass loss (Pawson 2008). In the same way that litter bags (and to a lesser extent humus bags (Adamczyk et al., 2019)) have been deployed across the worlds’ ecosystems to estimate litter decay rate (Zhang et al., 2008), the peatland community could make a concerted effort to directly measure peat mass loss to address this evidence gap. This cheap and scalable approach could help inform us of an important flux of carbon from the system. Alternatively, or in parallel, an expanded deployment of combined SRR and downstream sediment flux could infer wastage rates and expand this sparse dataset (Francis, 1990). While acknowledging the inherent topographical complexity of eroding peatland landscapes introducing additional uncertainty to eddy covariance measurement (Artz et



165 al.2022), we recommend additional large-scale monitoring of GHG fluxes from eroding bogs. Currently, there is only one available ‘flux tower’ observational data set from eroding peatland systems (Cairngorm Mountains, Scotland (Artz et al., 2022). Additional monitoring could therefore reduce uncertainty regarding the importance of bare peat for direct GHG fluxes in other climates, bare peat extents and management scenarios.

170 **Table 1: Estimated and measured fluxes from eroding blanket bogs. Surface retreat rate (SRR) is the median of rates from studies reviewed by Li et al (2018). Wastage Flux per area of bare is estimated from SRR by applying a UK average of 53% carbon in peat and 0.13 g cm⁻³ bulk density for peat soils between 30-100 cm (Frogbrook et al., 2009) and then assuming 35% of the lost carbon is through the gaseous loss pathway. The remaining 65 % is then assumed to be a POC flux per area of bare peat (assuming wind-eroded peat remains in the system and joins the fluvial POC**
 175 **flux). The wastage flux per area bare peat is scaled up to the catchment by assuming 15 % bare peat area combined with 85% of the catchment is ‘Modified bog’ which covers typical heather-dominated bogs and which carries an average emission factor of 2.51 t CO₂e ha⁻¹ yr⁻¹. The estimated POC flux is also normalised to catchment scale by assuming 15% bare peat cover (modified bog carries a POC emissions factor of 0). These data are compared to measured flux rates of CO₂ and POC from eroding bogs. NEE is measured by eddy covariance from a tower that’s**
 180 **footprint included peatland with approximately 15% bare peat (Artz et al., 2022). Measured fluxes of POC from peatland catchments are the median of values reviewed by (Li et al., 2018b), including at gauging stations and accumulating in reservoirs with eroding peatland catchments.**

	SRR	Wastage flux per area bare peat	POC flux per area bare peat	NEE Flux catchment scale	POC Flux catchment scale
Units	mm yr ⁻¹			tCO ₂ e ha ⁻¹ yr ⁻¹	
Estimated flux from erosion rates	18.9	16.7	31.1	4.6	4.7
Measured fluxes				3.6	0.7

185 **3 When peat erodes, how much is resedimented, oxidised or continues to be transported out of the erosion complex?**

Erosion systems in peatlands are complex, often starting with narrow ‘V’ shaped gullies which over time become ‘U’ or trapezoidal- shaped gullies as lateral erosion predominates once erosion reaches the base of the peat (Evans and Warburton, 2008), with eroded peat moving through this system on its way to the headwater streams (Fig. 3). Based on sediment flux data compiled by Li et al. (2018b), we calculated 0.7 tCO₂e ha⁻¹ yr⁻¹ loss of POC at the outlet of eroding blanket bogs (by applying a 53 % conversion factor for carbon content and a median sediment yield of 35 t km⁻² yr⁻¹). This rate is over six times lower than the POC flux that would be lost from peatlands based on our SRR rates estimates (Table 1). Due to scale-dependency of



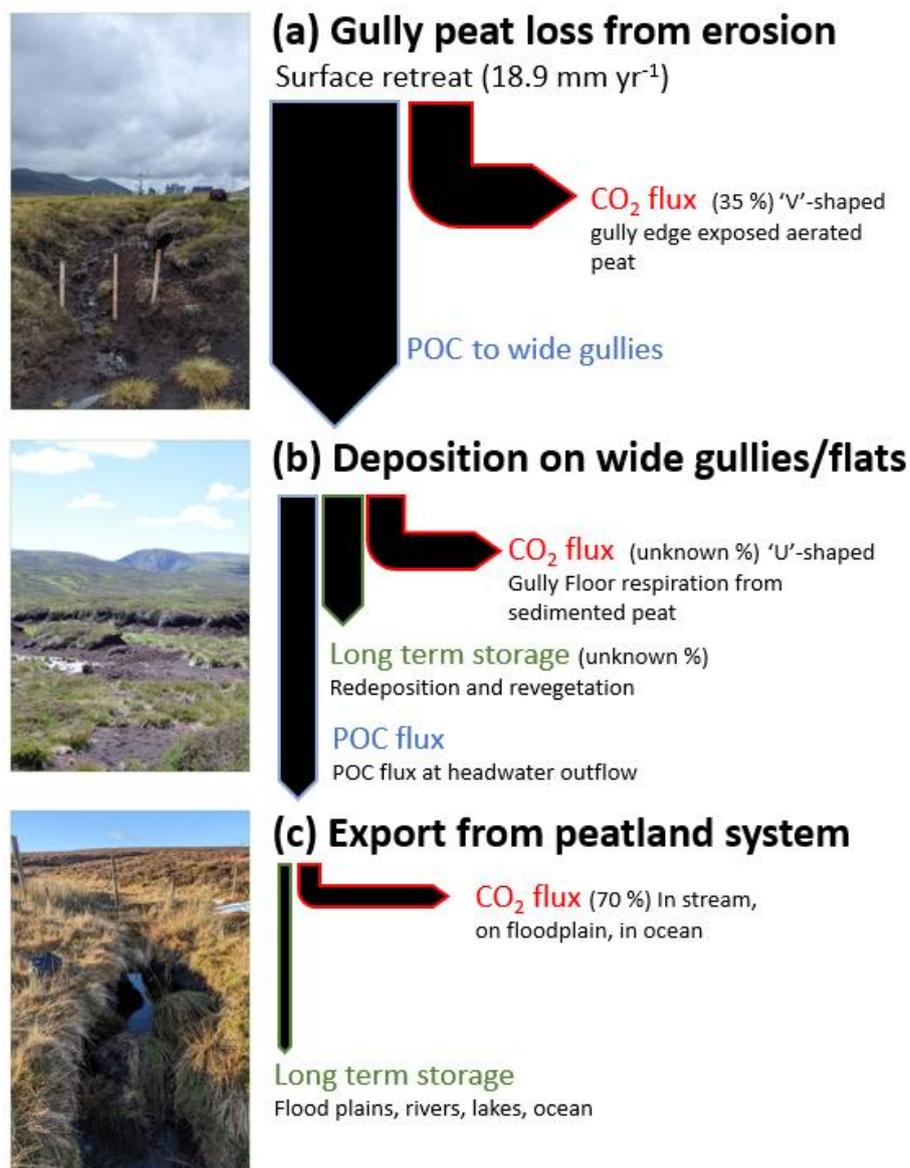
processes (see Li et al. (2018b) for a detailed discussion on this), direct comparison such as this should be cautioned against. Nevertheless, this difference raises important questions about how peat carbon is processed within the peatland system with potential important implications for GHG budgets in eroding peatland systems. Peat can transit through wider ‘U-shaped’ gullies in a matter of hours; however, a proportion is likely to resediment within the system for years where it will be further oxidised by the microbial community. How long peat sediment is retained in the system and the conditions it is exposed to will determine its decomposition rates, how much moves on out of the system and how much is retained for the long term (Fig.3).

Repeated drone-based remote sensing approaches are highlighting the amount of redeposition of peat sediment within peatlands. These approaches not only measure the geomorphic loss of peat on gully walls but also the vertical accumulation of peat in wider gullies downstream (Li et al., 2019; Glendell et al., 2017). One of the next important questions to answer is what is the mean residence time of peat particles within the system and how much decomposition occurs while the sediment is in this new environment? We know that areas that contain wide gullies are strong sources of CO₂ (Artz et al., 2022), as are areas of bare peat in former peat extraction sites (Rankin et al., 2018). However, bare gullies were measured to be only marginal sources of CO₂ with low metabolic activity in general (Dixon et al., 2014; Gatis et al., 2019). Using eddy covariance at high temporal resolution, conversely, Artz et al. (2022) observed peaks of ecosystem respiration at their eroded sites, suggesting that there are abiotic triggers that cause a pulse of CO₂ flux from the peat. Therefore, it is important to collect more data across a range of bare peat systems and conditions to understand the likely loss rates via CO₂ in these gully complexes.

Vegetation cover on the gully floor is a key control on the rate of resedimentation, as higher cover of vascular plants and bryophytes will hold up the flow of water and suspended sediment (Crowe et al., 2008; Harris and Baird, 2019; Milner et al., 2021), resulting in a reduced POC yield at the outflow (Evans et al., 2006). Erosion systems often reach a revegetated-base state with low POC flux rates at the outlet (Evans et al., 2006), however, it is not clear whether the trapped peat sediment is lost as CO₂ higher up in the peatland system. The turnover of resedimented material may depend on the vegetation cover of the gully floor, and its potential to trap freshly produced POC. Vegetated gullies were found to be ‘hotspots’ for ecosystem respiration in an eroding blanket bog (Mcnamara et al., 2008). Another naturally revegetated site had almost neutral CO₂ exchange as a result of high primary productivity being balanced by ecosystem respiration rates that were almost four times higher than in a bare gully system (Dixon et al., 2014). For both examples much of the ecosystem respiration flux will be from plant respiration, linked to vigorous growth associated with revegetated gully bases, however a significant amount could be from the resedimented peat. We understand that where peat is deposited on downstream floodplains (Alderson et al., 2019), it is turned over rapidly in aerobic conditions (Alderson et al., 2024) and up to 80% of POC deposited on a floodplain downstream of a peatland catchment will be mineralised to CO₂ within 30 years (Evans et al., 2013). Similar emission rates could be occurring in revegetated gully floors upstream of these floodplains. Microbial activity is likely to be lower in the gullies than downstream floodplains due to higher altitude (and therefore lower temperature), higher moisture (often saturating and anoxic)



and potentially different plant communities and associated microbial communities. However, CO₂ flux from redeposited POC within peatlands could still be substantial and this knowledge gap could be resolved by measuring the isotopic signature of the CO₂ produced to partition into autotrophic and heterotrophic sources.



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Figure 3: A schematic showing the transit of POC through multiple downstream systems with the pathways that carbon can take at different stages: converted to CO₂ (red), deposited in a long-term store (green) and transited to the next system as POC (blue). Percentage fluxes at each stage represent (a) best estimate of 35 % of SRR as 'wasting' CO₂ flux

from bare peat surfaces (Evans et al., 2006) and (c) 70 %, the post-peatland export POC- CO₂ conversion factor
235 determined by (Evans et al., 2013).

4 Concluding comments

Depending on the extent of bare peat within a peatland, and the local slope and wind conditions, erosion can be the dominant
pathway for carbon loss (Evans et al., 2006). Due to the complex biophysical processes and interactions that cascade from peat
240 erosion there is very high uncertainty around the emissions that occur as a result. There is a risk of both under- and
overestimating emissions from peat erosion, depending on the characteristics of the site. These uncertainties feed through to
uncertainties in national peatland emissions reporting (Ipcc, 2014) and estimates of emissions reductions that can be achieved
through bare peat restoration and revegetation. There are mismatches in data on sediment/carbon fluxes at certain points and
245 across scales on the journey of peat after it is eroded. These mismatches can be addressed by applying scalable measurements
at key junctures in the peat sediment's transition out of the peatland. These measurements should be biologically and
biogeochemically focussed on the processes that mineralise peat sediment to CO₂, and ultimately cause the emissions that we
need to quantify.

Author Contribution

250 Conceptualisation: TP & RA. Writing – review & editing: All authors.

Competing interests

The authors declare that they have no conflict of interest

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255 References

Adamczyk, B., Sietio, O. M., Strakova, P., Prommer, J., Wild, B., Hagner, M., Pihlatie, M., Fritze, H., Richter, A., and
Heinonsalo, J.: Plant roots increase both decomposition and stable organic matter formation in boreal forest soil, Nat Commun,
10, 3982, 10.1038/s41467-019-11993-1, 2019.



- 260 Alderson, D. M., Evans, M. G., Garnett, M. H., and Worrall, F.: Aged carbon mineralisation from headwater peatland floodplains in the Peak District, UK, *Geomorphology*, 461, 109271, <https://doi.org/10.1016/j.geomorph.2024.109271>, 2024.
- Alderson, D. M., Evans, M. G., Rothwell, J. J., Rhodes, E. J., and Boulton, S.: Geomorphological controls on fluvial carbon storage in headwater peatlands, *Earth Surface Processes and Landforms*, 44, 1675-1693, 10.1002/esp.4602, 2019.
- Artz, R. R. E., Coyle, M., Donaldson-Selby, G., and Morrison, R.: Net carbon dioxide emissions from an eroding Atlantic blanket bog, *Biogeochemistry*, 159, 233-250, 10.1007/s10533-022-00923-x, 2022.
- 265 Artz, R. R. E., Chapman, S. J., Jean Robertson, A. H., Potts, J. M., Laggoun-Défarge, F., Gogo, S., Comont, L., Disnar, J.-R., and Francez, A.-J.: FTIR spectroscopy can be used as a screening tool for organic matter quality in regenerating cutover peatlands, *Soil Biology and Biochemistry*, 40, 515-527, 10.1016/j.soilbio.2007.09.019, 2008.
- Biester, H., Knorr, K. H., Schellekens, J., Basler, A., and Hermanns, Y. M.: Comparison of different methods to determine the degree of peat decomposition in peat bogs, *Biogeosciences*, 11, 2691-2707, 10.5194/bg-11-2691-2014, 2014.
- 270 Clay, G. D., Dixon, S., Evans, M. G., Rowson, J. G., and Worrall, F.: Carbon dioxide fluxes and DOC concentrations of eroding blanket peat gullies, *Earth Surface Processes and Landforms*, 37, 562-571, 10.1002/esp.3193, 2012.
- Cotterill, D., Stott, P., Christidis, N., and Kendon, E.: Increase in the frequency of extreme daily precipitation in the United Kingdom in autumn, *Weather and Climate Extremes*, 33, 100340, <https://doi.org/10.1016/j.wace.2021.100340>, 2021.
- Crowe, S., Evans, M., and Allott, T.: Geomorphological controls on the re-vegetation of erosion gullies in blanket peat: implications for bog restoration, *Mires & Peat*, 3, 2008.
- 275 Cumming, A. M. J.: Multi-annual carbon flux at an intensively cultivated lowland peatland in East Anglia, UK, University of Leicester, 2018.
- Daniels, S. M., Agnew, C. T., Allott, T. E. H., and Evans, M. G.: Water table variability and runoff generation in an eroded peatland, South Pennines, UK, *Journal of Hydrology*, 361, 214-226, 10.1016/j.jhydrol.2008.07.042, 2008.
- 280 Defrenne, C. E., Moore, J. A. M., Tucker, C. L., Lamit, L. J., Kane, E. S., Kolka, R. K., Chimner, R. A., Keller, J. K., and Lilleskov, E. A.: Peat loss collocates with a threshold in plant-mycorrhizal associations in drained peatlands encroached by trees, *New Phytologist*, 240, 412-425, <https://doi.org/10.1111/nph.18954>, 2023.
- Dixon, S. D., Qassim, S. M., Rowson, J. G., Worrall, F., Evans, M. G., Boothroyd, I. M., and Bonn, A.: Restoration effects on water table depths and CO₂ fluxes from climatically marginal blanket bog, *Biogeochemistry*, 118, 159-176, 2014.
- 285 Evans, C., Artz, R., Burden, A., Clilverd, H., Freeman, B., Heinemeyer, A., Lindsay, R., Morrison, R., Potts, J., and Reed, M.: Aligning the peatland code with the UK peatland inventory, 2022.
- Evans, C., Artz, R., Moxley, J., Smyth, M.-A., Taylor, E., Archer, E., Burden, A., Williamson, J., Donnelly, D., and Thomson, A.: Implementation of an emissions inventory for UK peatlands, Centre for Ecology and Hydrology, 2017.
- Evans, C., Allott, T., Billett, M., Burden, A., Chapman, P., Dinsmore, K., Evans, M., Freeman, C., Goulsbra, C., Holden, J., 290 Jones, D., Jones, T., Moody, C., Palmer, S., and Worrall, F.: Towards the estimation of CO₂ emissions associated with POC fluxes from drained and eroding peatlands., Centre for Ecology and Hydrology, Bangor, 2013.
- Evans, C. D., Callaghan, N., Jaya, A., Grinham, A., Sjogersten, S., Page, S. E., Harrison, M. E., Kusin, K., Kho, L. K., Ledger, M., Evers, S., Mitchell, Z., Williamson, J., Radbourne, A. D., and Jovani-Sancho, A. J.: A Novel Low-Cost, High-Resolution Camera System for Measuring Peat Subsidence and Water Table Dynamics, *Frontiers in Environmental Science*, 9, 10.3389/fenvs.2021.630752, 2021a.
- 295 Evans, C. D., Peacock, M., Baird, A. J., Artz, R. R. E., Burden, A., Callaghan, N., Chapman, P. J., Cooper, H. M., Coyle, M., Craig, E., Cumming, A., Dixon, S., Gauci, V., Grayson, R. P., Helfter, C., Heppell, C. M., Holden, J., Jones, D. L., Kaduk, J., Levy, P., Matthews, R., McNamara, N. P., Misselbrook, T., Oakley, S., Page, S. E., Rayment, M., Ridley, L. M., Stanley, K. M., Williamson, J. L., Worrall, F., and Morrison, R.: Overriding water table control on managed peatland greenhouse gas emissions, *Nature*, 593, 548-552, 10.1038/s41586-021-03523-1, 2021b.
- 300 Evans, M. and Warburton, J.: Geomorphology of Upland Peat: Erosion, Form and Landscape Change, *Geomorphology of Upland Peat: Erosion, Form and Landscape Change*, 1-262, 10.1002/9780470798003, 2008.
- Evans, M. and Warburton, J.: Geomorphology of upland peat: erosion, form and landscape change, John Wiley & Sons, Chichester, England 2011.
- 305 Evans, M., Warburton, J., and Yang, J.: Eroding blanket peat catchments: Global and local implications of upland organic sediment budgets, *Geomorphology*, 79, 45-57, 10.1016/j.geomorph.2005.09.015, 2006.
- Francis, I. S.: Blanket Peat Erosion In A Mid-wales Catchment During 2 Drought Years, *Earth Surface Processes and Landforms*, 15, 445-456, 10.1002/esp.3290150507, 1990.



- 310 Frogbrook, Z. L., Bell, J., Bradley, R. I., Evans, C., Lark, R. M., Reynolds, B., Smith, P., and Towers, W.: Quantifying terrestrial carbon stocks: examining the spatial variation in two upland areas in the UK and a comparison to mapped estimates of soil carbon, *Soil Use and Management*, 25, 320-332, <https://doi.org/10.1111/j.1475-2743.2009.00232.x>, 2009.
- Gatis, N., Benaud, P., Ashe, J., Luscombe, D. J., Grand-Clement, E., Hartley, I. P., Anderson, K., and Brazier, R. E.: Assessing the impact of peat erosion on growing season CO₂ fluxes by comparing erosional peat pans and surrounding vegetated hags, *Wetlands Ecology and Management*, 27, 187-205, 10.1007/s11273-019-09652-9, 2019.
- 315 Glendell, M., McShane, G., Farrow, L., James, M. R., Quinton, J., Anderson, K., Evans, M., Benaud, P., Rawlins, B., Morgan, D., Jones, L., Kirkham, M., DeBell, L., Quine, T. A., Lark, M., Rickson, J., and Brazier, R. E.: Testing the utility of structure-from-motion photogrammetry reconstructions using small unmanned aerial vehicles and ground photography to estimate the extent of upland soil erosion, *Earth Surface Processes and Landforms*, - 42, - 1871, 2017.
- Harris, A. and Baird, A. J.: Microtopographic Drivers of Vegetation Patterning in Blanket Peatlands Recovering from Erosion, *Ecosystems*, 22, 1035-1054, 10.1007/s10021-018-0321-6, 2019.
- 320 Hooijer, A., Page, S., Jauhainen, J., Lee, W. A., Lu, X. X., Idris, A., and Anshari, G.: Subsidence and carbon loss in drained tropical peatlands, *Biogeosciences*, 9, 1053-1071, 2012.
- Hutchinson, J. N.: The Record of Peat Wastage in the East Anglian Fenlands at Holme Post, 1848-1978 A.D, *Journal of Ecology*, 68, 229-249, 10.2307/2259253, 1980.
- 325 IPCC: 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands, IPCC, Switzerland, 2014.
- Kagawa, H., Yamamoto, K., Sutikno, S., Haidar, M., Basir, N., Koyama, A., Kanno, A., Akamatsu, Y., and Suzuki, M.: Estimation of particulate organic carbon export to the ocean from lateral degradations of tropical peatland coasts, *EGUsphere*, 2024, 1-34, 2024.
- 330 Lamoureux, S. F., Lafrenière, M. J., and Favaro, E. A.: Erosion dynamics following localized permafrost slope disturbances, *Geophysical Research Letters*, 41, 5499-5505, <https://doi.org/10.1002/2014GL060677>, 2014.
- Lantuit, H. and Pollard, W. H.: Fifty years of coastal erosion and retrogressive thaw slump activity on Herschel Island, southern Beaufort Sea, Yukon Territory, Canada, *Geomorphology*, 95, 84-102, <https://doi.org/10.1016/j.geomorph.2006.07.040>, 2008.
- 335 Lantuit, H., Overduin, P. P., Couture, N., Wetterich, S., Aré, F., Atkinson, D., Brown, J., Cherkashov, G., Drozdov, D., Forbes, D. L., Graves-Gaylord, A., Grigoriev, M., Hubberten, H.-W., Jordan, J., Jorgenson, T., Ødegård, R. S., Ogorodov, S., Pollard, W. H., Rachold, V., Sedenko, S., Solomon, S., Steenhuisen, F., Streletskaia, I., and Vasiliev, A.: The Arctic Coastal Dynamics Database: A New Classification Scheme and Statistics on Arctic Permafrost Coastlines, *Estuaries and Coasts*, 35, 383-400, 10.1007/s12237-010-9362-6, 2012.
- Li, C., Holden, J., and Grayson, R.: Effects of Needle Ice on Peat Erosion Processes During Overland Flow Events, *Journal of Geophysical Research: Earth Surface*, 123, 2107-2122, <https://doi.org/10.1029/2017JF004508>, 2018a.
- 340 Li, C., Grayson, R., Holden, J., and Li, P.: Erosion in peatlands: Recent research progress and future directions, *Earth-Science Reviews*, 185, 870-886, 10.1016/j.earscirev.2018.08.005, 2018b.
- Li, C. J., Grayson, R., Smith, M., and Holden, J.: Patterns and drivers of peat topographic changes determined from Structure-from-Motion photogrammetry at field plot and laboratory scales, *Earth Surface Processes and Landforms*, 44, 1274-1294, 10.1002/esp.4571, 2019.
- 345 Li, P., Holden, J., Irvine, B., and Mu, X.: Erosion of Northern Hemisphere blanket peatlands under 21st-century climate change, *Geophysical Research Letters*, 44, 3615-3623, <https://doi.org/10.1002/2017GL072590>, 2017.
- Macfarlane, F., Robb, C., Coull, M., McKeen, M., Wardell-Johnson, D., Miller, D., Parker, T. C., Artz, R. R. E., Matthews, K., and Aitkenhead, M. J.: A deep learning approach for high-resolution mapping of Scottish peatland degradation, *European Journal of Soil Science*, 75, e13538, <https://doi.org/10.1111/ejss.13538>, 2024.
- 350 McNamara, N. P., Plant, T., Oakley, S., Ward, S., Wood, C., and Ostle, N.: Gully hotspot contribution to landscape methane (CH₄) and carbon dioxide (CO₂) fluxes in a northern peatland, *Science of The Total Environment*, 404, 354-360, <https://doi.org/10.1016/j.scitotenv.2008.03.015>, 2008.
- Milner, A. M., Baird, A. J., Green, S. M., Swindles, G. T., Young, D. M., Sanderson, N. K., Timmins, M. S. I., and Galka, M.: A regime shift from erosion to carbon accumulation in a temperate northern peatland, *Journal of Ecology*, 109, 125-138, 10.1111/1365-2745.13453, 2021.



- Palmer, S. M., Evans, C. D., Chapman, P. J., Burden, A., Jones, T. G., Allott, T. E. H., Evans, M. G., Moody, C. S., Worrall, F., and Holden, J.: Sporadic hotspots for physico-chemical retention of aquatic organic carbon: from peatland headwater source to sea, *Aquatic Sciences*, 78, 491-504, 10.1007/s00027-015-0448-x, 2016.
- 360 Pawson, R.: Assessing the role of particulates in the fluvial organic carbon flux from eroding peatland systems, Faculty of Humanities, University of Manchester, 304 pp., 2008.
- Pizano, C., Barón, A. F., Schuur, E. A. G., Crummer, K. G., and Mack, M. C.: Effects of thermo-erosional disturbance on surface soil carbon and nitrogen dynamics in upland arctic tundra, *Environmental Research Letters*, 9, 075006, 10.1088/1748-9326/9/7/075006, 2014.
- 365 Rankin, T., Strachan, I. B., and Strack, M.: Carbon dioxide and methane exchange at a post-extraction, unrestored peatland, *Ecological Engineering*, 122, 241-251, 2018.
- Robinson, C. H., Ritson, J. P., Alderson, D. M., Malik, A. A., Griffiths, R. I., Heinemeyer, A., Gallego-Sala, A. V., Quillet, A., Robroek, B. J., and Evans, C.: Aspects of microbial communities in peatland carbon cycling under changing climate and land use pressures, *Mires and Peat*, 29, 2, 2023.
- 370 Selkirk, J. M. and Saffigna, L. J.: Wind and Water Erosion of a Peat and Sand Area on Subantarctic Macquarie Island, Arctic, Antarctic, and Alpine Research, 31, 412-420, 10.1080/15230430.1999.12003326, 1999.
- Sloan, T. J., Payne, R. J., Anderson, A. R., Gilbert, P., Mauquoy, D., Newton, A., and Andersen, R.: Ground surface subsidence in an afforested peatland fifty years after drainage and planting, *Mires and Peat*, 2019.
- 375 Swindles, G. T., Morris, P. J., Mullan, D., Watson, E. J., Turner, T. E., Roland, T. P., Amesbury, M. J., Kokfelt, U., Schoning, K., Pratte, S., Gallego-Sala, A., Charman, D. J., Sanderson, N., Garneau, M., Carrivick, J. L., Woulds, C., Holden, J., Parry, L., and Galloway, J. M.: The long-term fate of permafrost peatlands under rapid climate warming, *Scientific Reports*, 5, 17951, 10.1038/srep17951, 2015.
- Warburton, J.: Wind-splash erosion of bare peat on UK upland moorlands, *Catena*, 52, 191-207, 10.1016/s0341-8162(03)00014-6, 2003.
- 380 Williamson, J., Rowe, E., Reed, D., Ruffino, L., Jones, P., Dolan, R., Buckingham, H., Norris, D., Astbury, S., and Evans, C. D.: Historical peat loss explains limited short-term response of drained blanket bogs to rewetting, *Journal of Environmental Management*, 188, 278-286, <https://doi.org/10.1016/j.jenvman.2016.12.018>, 2017.
- Wilson, P., Clark, R., McAdam, J. H., and Cooper, E. A.: Soil erosion in the Falkland Islands: an assessment, *Applied Geography*, 13, 329-352, [https://doi.org/10.1016/0143-6228\(93\)90036-Z](https://doi.org/10.1016/0143-6228(93)90036-Z), 1993.
- 385 Zhang, D., Hui, D., Luo, Y., and Zhou, G.: Rates of litter decomposition in terrestrial ecosystems: global patterns and controlling factors, *Journal of Plant Ecology*, 1, 85-93, 10.1093/jpe/rtn002, 2008.
- Zhou, Y., Evans, C. D., Chen, Y., Chang, K. Y., and Martin, P.: Extensive remineralization of peatland-derived dissolved organic carbon and ocean acidification in the Sunda Shelf Sea, Southeast Asia, *Journal of Geophysical Research: Oceans*, 126, e2021JC017292, 2021.

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