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Shallow peatlands as sentinels of climate change

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1. Introduction

Northern peatlands are a globally important carbon reserve, storing 450–610 Gt of carbon (Strack 2023). The long-term net carbon sink function of northern peatlands is largely the result of peatland plant productivity exceeding peat and litter decomposition and combustion (Rydin *et al* 2013), controlled by high peat moisture content and water tables consistently close to the surface. However, as air temperatures rise with climate change, northern peatlands are expected to experience an increase in evapotranspiration that exceeds increases in precipitation, leading to enhanced drying and greater water table depths (Helbig *et al* 2020). There is a concern that these drier conditions will increase peat decomposition, moss moisture stress (Strack 2023), and combustion losses of peat carbon (Wilkinson *et al* 2023), especially in peatlands with negligible surface or groundwater supply, thereby placing the global peatland carbon sink at risk (Wilkinson *et al* 2023). Yet, there is considerable uncertainty associated with the interaction between climate change and peatland carbon accumulation, decomposition, and combustion, and ultimately the integrity of the peat carbon sequestration function (Loisel *et al* 2021). This uncertainty is not unexpected as peatlands are complex, dynamic systems (e.g. Belyea and Baird 2006), which have numerous interconnected feedback mechanisms that ameliorate large fluctuations in water table depth and maintain high moisture content in near-surface peat (Waddington *et al* 2015). Due to the complexity of these interacting feedbacks, inadequacies in the experimental or conceptual representation of climate change in field and modelling studies can trigger cascading effects that can alter projections of whether a peatland will function as a future carbon sink or source (Waddington *et al* 2015, Strack 2023). As peatlands are increasingly considered for nature-based climate solutions, it is essential to confidently evaluate their trajectory and future function to ensure that conservation and restoration efforts effectively support long-term carbon storage (Harris *et al* 2022).

The efficacy of internal regulatory mechanisms has contributed to the persistence and resilience of pristine peatland carbon stocks over millennia (Loisel *et al* 2021, Strack 2023). Nonetheless, there are limits to the capacity of these feedbacks to moderate the influence of exogenous drivers such as climate change (Waddington *et al* 2015). In pristine, laterally-extensive, deep peatlands, the capacity to maintain homeostasis is often sufficient to prevent destabilization from external disturbance like drought and wildfire (Wilkinson *et al* 2020, Moore *et al* 2021). These peatlands recover quickly and remain resilient, however, not all peatlands possess the same regulatory capacity nor exhibit the same vulnerabilities. Increasingly, the strength of these feedback mechanisms has been associated with water storage (Waddington *et al* 2015). Given the limited water storage capacity of shallow peatlands, they should exhibit diminished resilience and a greater sensitivity to external stressors (e.g. Moore *et al* 2021), reflecting the precarious internal balance between regulatory (negative) and destabilizing (positive) feedbacks.

Yet, shallow peatlands have been understudied relative to deeper systems, which is partly a reflection of the subjective approaches used to distinguish peatlands from mineral wetlands (Rydin *et al* 2013). The distinction of peatlands from other types of wetlands varies between jurisdictions and commonly takes the form of a threshold organic soil depth (Lourenco *et al* 2023). There are growing calls for these criteria to be adjusted to accommodate shallow peatlands, with Lourenco *et al* (2023) recommending a 0.1 m threshold, which we concur with and adopt here. Nevertheless, these ecosystems exist along a continuum, and as a result, systems that exhibit many functional attributes of a peatland have not been classified and, as such, have not been studied from peatland ecohydrological or carbon biogeochemical perspectives. Despite these functional similarities, shallow peatlands demonstrate meaningful differences in ecohydrological behaviour from their deeper counterparts. For example, autogenic feedback mechanisms operating in shallow peatlands appear to have a comparatively limited capacity to regulate their environment, predominantly owing to a water table that frequently drops below the bottom of the peat profile, markedly limiting upward water movement (Moore *et al* 2021). Consequently, shallow peatlands have exhibited greater vulnerability to external environmental pressures, experiencing higher moss moisture stress (Moore *et al* 2021), lower net carbon sequestration (McDonald *et al* 2023), and higher burn severity (Wilkinson *et al* 2020). These differences in ecohydrological behaviour suggest that shallow peatlands may function near critical ecohydrological thresholds, where their ability to maintain key functions is more easily disrupted. Shallow peatlands are, therefore, likely operating near the margins of their survivability.

Peatland researchers have adopted numerous approaches (modelling, mesocosm and field experiments, paleoecological studies) to discern when peatlands are near resilience thresholds. Quantifying these thresholds allows researchers to identify when small changes in external drivers could push shallow peatlands past a tipping point (e.g. Wilkinson *et al* 2020), potentially leading to irreversible change and a shift to rapid carbon loss (e.g. Ise *et al* 2008). We suggest that shallow peatlands offer a unique opportunity and valuable tool to study the thresholds and boundaries of peatland resilience.

Shifting patterns of water availability may nudge once-resilient peatlands into new regimes of ecohydrological stress. When stressed, the potential to exceed the limits of peatland elasticity increases, where short-term feedback mechanisms can no longer prevent irreversible changes to peatland structure and function. If stress persists or intensifies, then the boundary of peatland resilience may be reached, causing a deterioration towards a new equilibrium, which could include a non-peatland state (Harris *et al* 2022). Climate change is anticipated to enhance drying in northern peatlands (Helbig *et al* 2020), and increase the frequency, severity, and areal extent of wildfire (Wilkinson *et al* 2023). As such, we suggest that the contemporary biogeochemical and hydrological behaviour of shallow peatlands presages the future behaviour of deep peatlands (figure 1).

Here we advocate for the study of shallow peatlands to better understand the effect of climate change on peatlands by highlighting four critical research questions.

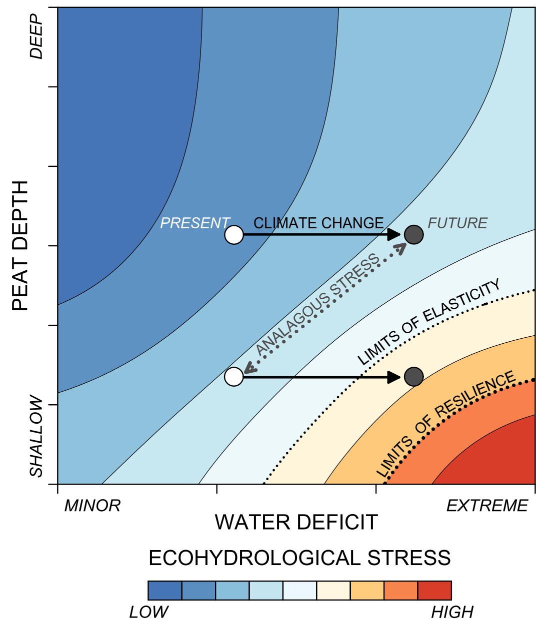

Figure 1. Conceptual diagram illustrating ecohydrological stress as a function of peat depth and water deficit, which we define as precipitation minus evapotranspiration. Open circles represent contemporary conditions, filled circles represent future conditions. The limits of elasticity and limits of resilience denote theoretical boundaries in the stability of the peatland ecohydrological regime, where the former represents the onset of permanent structural changes in peatland form and function and the latter represents a shift to a new ecosystem trajectory.

1) What is the spatial distribution and environmental envelope of shallow peatlands?
2) How strong are regulatory mechanisms in shallow peatlands?
3) Where are the tipping points in shallow peatland resilience?
4) What metrics can discern when peatlands have exceeded thresholds of resilience?

2. Shallow peatland spatial distribution and environmental envelope

The dearth of research on shallow peatlands has meant that the global spatial distribution of these ecosystems remains unknown. Consequently, not only is their value on the landscape from an ecological and carbon sequestration perspective uncertain but the hydrological conditions that sustain these marginal systems remain poorly understood. We encourage regional and national peatland inventories to identify and contrast the hydroclimatic and hydrogeomorphic settings that support shallow peatlands, compared to their deeper counterparts. Characterizing the hydroclimatic and hydrogeomorphic settings of shallow peatlands will contribute to an understanding of the envelope of hydrological conditions that will enable peatland development and inform the (climatological) boundaries of their resilience. This will facilitate the interpretation of climate change projections as a shift in the typical level of ecohydrological stress experienced by a peatland, and allow for cross-regional comparisons between fundamentally different peat-forming regions.

3. Shallow peatland regulatory mechanisms

Conceptual frameworks of regulatory and destabilizing feedback mechanisms have been developed for northern peatlands (Waddington *et al* 2015), however the strength of these feedback mechanisms relative to each other and how they differ with peatland morphology remains unclear. We urge researchers to investigate the sign and strength of peatland feedback mechanisms in shallow peatlands, which consistently experience water stress with greater intensity, frequency and duration. During periods of pronounced water stress, some regulatory mechanisms may reach the limits of their efficacy (Moore *et al* 2021). We theorize that shallow systems will reach any such limits more quickly, with deleterious effects exacerbated by climate change. Negative outcomes include the activation of feedback mechanisms that reflect long-term deviations from optimal conditions, like those that cause irreversible changes to the peat structure (Whittington and Price 2006) or the proliferation of non-peat forming vegetation (e.g. Kettridge *et al* 2015). We will gain considerable understanding by contrasting the strength of different feedback mechanisms between shallow and deep systems. Although little direct study has been done on feedback mechanisms in shallow peatlands, research comparing peatland margins and middles (e.g. Wilkinson *et al* 2019) and ecohydrological modelling (Moore *et al* 2021) have provided limited insight into the relative strength of some feedbacks in shallow versus deep ecosystems. For example, the water table depth—moss species moisture retention feedback (see Waddington *et al* 2015 for details) has been shown to be a weaker negative feedback in shallow peatlands relative to deep peatlands (Kettridge *et al* 2015, Moore *et al* 2021). Yet, still other feedbacks have not been studied and thus represent crucial missing links in our conceptual understanding of peatland ecohydrological resilience. These include the moss productivity feedback, peat decomposition feedback, and moss surface resistance and albedo feedback, which we feel have the greatest potential to steer peatland ecohydrological function while also having high uncertainty.

4. Shallow peatland tipping points

The net interaction between peatland feedback mechanisms may manifest threshold behaviour in the ecohydrological functioning and resilience of stressed systems (e.g. Nijp *et al* 2017). When the efficacy of multiple regulatory mechanisms are compromised, vulnerability to disturbance will increase disproportionately and the ability to maintain critical functions like carbon sequestration may be disrupted (e.g. Kettridge *et al* 2015). Furthermore, enhanced susceptibility to wildfire means more frequent and more severe burns (Wilkinson *et al* 2020). A shorter interval between burns and greater depth of burn may result in a progressive loss of stored carbon, as peatlands may not be able to recover quickly enough from wildfire (Wilkinson *et al* 2023). Ultimately, this could shift these ecosystems toward a degraded peatland state. Therefore, investigating shallow systems, which may already be on the verge of instability, offers an important opportunity to evaluate the tipping points that manifest from the cumulative effect of individual feedbacks.

5. Shallow peatland ecohydrological metrics

Untangling the contribution of the numerous interconnected feedback mechanisms operating within peatlands to overall ecohydrological resilience will require intensive investigation, consistent with the vision of Webster *et al* (2025) of establishing a network of peatland 'supersites'. Evaluating, detecting, and quantifying tipping points in peatland ecohydrological resilience will necessitate the integration of multiple measurements of peatland function, which precludes a diffuse monitoring strategy. Although the water table is frequently used to distill a host of complex hydrological processes, numerous studies have identified the importance of near-surface soil water tension (e.g. Kettridge *et al* 2021) and soil moisture (e.g. Nijp *et al* 2017) for characterizing thresholds in peatland feedback mechanisms and providing process-based insights. These metrics are valuable indicators of short-term ecohydrological stress, yet they capture only part of the system's response to environmental change. In contrast, the net carbon balance integrates the cumulative effects of hydrological, pedological, biological, and climatic interactions, offering a more holistic measure of peatland function over time. As such, while soil water tension and moisture provide essential mechanistic understanding, the carbon balance fundamentally reflects the resilience and stability of peatlands in a changing climate. In addition to contemporary measurements of the carbon balance, palaeoenvironmental proxies from peat cores may also help us understand the limits of peatland elasticity and resilience. Hiatuses in peat accumulation, which can be identified from age-depth relationships, can sometimes indicate past changes in the carbon balance due to combustion from wildfire, increased decomposition, or reduced production, resulting in phases of net peat carbon loss—episodes during which the limits of elasticity have been exceeded (e.g. van der Linden *et al* 2014). Shallow peatlands will be more susceptible to these interruptions in peat accumulation and will be partly responsible for their contemporary depth. Buried peat layers can even shed light on former peatlands that have exceeded their limits for resilience, and have been replaced by other ecosystems (Treat *et al* 2019).

Ultimately, evaluating the trajectory of deep peatlands and their crucial carbon stock will require a combination of contemporary experiments, modelling, and palaeoenvironmental techniques. We suggest these would be most effectively applied to shallow peatlands, which currently experience a level of ecohydrological stress that will become increasingly common in the future, allowing them to act as sentinels of climate change.

Data availability statement

No new data were created or analyzed in this study.

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Author contributions

O F S, P A M, F A K, and J M W conceptualized, wrote, and edited the paper. P J M wrote and edited the paper. O F S and J M W conceptualized, designed, and created the figure.

Conflict of interest

The authors declare no competing interests.

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