Article:

Heinemeyer, Andreas orcid.org/0000-0003-3151-2466 and Ashby, Mark (2023) Prescribed Fire in UK Heather-Dominated Blanket Bog Peatlands:A Critical Review of "Carbon Storage and Sequestration by Habitat: A Review of the Evidence (Second Edition)" by Gregg et al., 2021. Fire. 204. ISSN: 2571-6255

https://doi.org/10.3390/fire6050204

fire

MDPI

Review

Prescribed Fire in UK Heather-Dominated Blanket Bog Peatlands: A Critical Review of "Carbon Storage and Sequestration by Habitat: A Review of the Evidence (Second Edition)" by Gregg et al., 2021

Andreas Heinemeyer [1,*] and Mark A. Ashby [2]

[1] Department of Environment & Geography, Stockholm Environment Institute, University of York, York YO10 5NG, UK
[2] School of Geography, Geology and Environment, University of Keele, Newcastle-under-Lyme ST5 5BG, UK
* Correspondence: andreas.heinemeyer@york.ac.uk

Abstract: Peatlands are a vast global carbon store. Both climate change and management have shaped peatlands over millennia, sometimes negatively, sometimes positively. Across the globe, prescribed fire is an important and well-recognised vegetation management tool used to promote biodiversity, increase habitat heterogeneity and mitigate uncontrolled wildfires. However, in the UK, there is an ongoing debate about the efficacy and legitimacy of using prescribed fire as a vegetation management tool. The debate centres around the extent to which prescribed burning is associated with a decline in habitat status and ecological function, especially in relation to carbon storage within heather-dominated blanket bog peatlands. Robust reviews of the evidence base are thus required to disentangle this debate and inform land management policies that ensure the protection and enhancement of blanket bog ecological functioning. Here, we critically review "Carbon storage and sequestration by habitat: a review of the evidence (second edition)" by Gregg et al., 2021. We see the value in synthesising the evidence on this topic but question the methodological approach used by Gregg et al. Another concern is their misrepresentation of evidence relating to prescribed burning impacts on blanket bog ecosystems and carbon budgets. We highlight these issues by focusing on the relevant peatland sections within the review by Gregg et al. and conclude by making a series of recommendations to improve the review's scientific robustness and, thereby, its value to academics, land managers and policymakers.

Keywords: carbon storage; carbon sequestration; blanket bog; evidence-based policy; net ecosystem carbon balance; peatlands; prescribed fire; vegetation burning; upland land management

Citation: Heinemeyer, A.; Ashby, M.A. Prescribed Fire in UK Heather-Dominated Blanket Bog Peatlands: A Critical Review of "Carbon Storage and Sequestration by Habitat: A Review of the Evidence (Second Edition)" by Gregg et al., 2021. *Fire* **2023**, *6*, 204. https://doi.org/10.3390/fire6050204

Academic Editor: Grant Williamson

Received: 4 April 2023
Revised: 24 April 2023
Accepted: 4 May 2023
Published: 15 May 2023

1. Introduction

In 2021, Natural England published an updated version of their 2012 evidence review on carbon storage and sequestration by habitat [1] (herein Gregg et al.). Whilst we welcome this attempt to synthesise the evidence on this topic, we are concerned about the lack of a transparent and objective review methodology. We are especially concerned about the misrepresentation of the evidence relating to prescribed fire impacts on blanket bog ecosystems and net ecosystem carbon budgets (NECB). In the UK, prescribed fire is primarily used for grouse moor management. Consequently, it has become a contentious and controversial topic of debate in the public, academic and policymaking arena [2–10]. In contrast, outside the UK, prescribed fire is considered a valuable habitat and vegetation management tool, especially for reducing fuel loads and, thereby, wildfire risk and damage [3–5,11–13].

Here, we review and provide constructive responses to the methodological issues within Gregg et al. and their misrepresentation of prescribed fire impacts on blanket bog. Consequently, our response focuses on Sections 1.1–1.7 and 4.1–4.3 of Gregg et al.

(pp. 2–8 and 95–115, respectively). We conclude by outlining a series of recommendations. By doing so, we aim to enhance future iterations of Gregg et al. to the benefit of academics, land managers and policymakers. We also call on experts to use a similar approach and review the other sections in Gregg et al. to further enhance its scientific utility. To aid interpretation, we have provided definitions of key terms within Box 1.

Box 1. Definitions and their corresponding references as provided inside brackets [14,15].

Blanket bog [14,15]**:**
Blanket bogs are largely ombrotrophic (i.e., rainfed) peatland habitats that form in the UK's cool and wet upland environments. Inhibited surface drainage, high rainfall and low evapotranspiration rates support water-logged conditions and enable peat development in damp hollows and over large areas of undulating ground. Peat depth varies but usually lies between 0.5–3 metres, although the mean maximum peat depth is estimated to be about 6 metres. One characteristic distinguishing blanket bogs from other peatland ecosystems is the vegetation communities they support, which include species such as *Calluna vulgaris*, *Erica tetralix*, *Trichophorum cespitosum*, *Eriophorum* species and several *Sphagnum* species. However, there is no agreed-upon minimum peat depth that can support typical blanket bog vegetation communities. Blanket bogs also have water tables at or near the soil surface and variable surface patterning, ranging from a relatively smooth surface, with the occasional *Sphagnum* hummock and *Eriophorum vaginatum* tussock, to a suite of bog pools and ridges.

Carbon sequestration:
The removal and storage of atmospheric carbon within a reservoir (e.g., peat soils). In natural systems, photosynthesising 'green' plants remove carbon from the atmosphere, which is sequestered within the vegetation biomass and transferred into dead organic matter, accumulating but also decomposing over time.

Carbon stocks [15]**:**
The quantity of (organic) carbon stored in a reservoir, such as vegetation biomass or peat soils. It is usually expressed as the (organic) carbon content per unit area and, for soils, depth.

Grouse moor management [16–18]**:**
Grouse moor management uses various tools to produce a shootable surplus of red grouse *Lagopus lagopus scotica*. The tools used include the legal control of generalist predators (e.g., red foxes, stoats, and carrion crows), disease regulation (e.g., the application of medicated grit) and vegetation control (e.g., prescribed burning of heather). Red grouse are an upland species, which means grouse moors are restricted to the British uplands, mainly in England and Scotland. Therefore, they overlap considerably with blanket bog habitats.

Holocene [19]**:**
The current geological epoch, which began approximately 11,650 cal years before the present.

Net ecosystem carbon balance (NECB) [20]**:**
The net balance of carbon inputs from photosynthesis and losses from decomposition (as CO_2 and CH_4) in addition to fluvial export (dissolved and particulate organic carbon), which sometimes also considers gains/losses from sedimentation/erosion and stream outgassing (as CO_2 and CH_4). Carbon uptake by vegetation is via Gross Primary Productivity (GPP) and release via ecosystem respiration (Reco), with the difference in CO_2 fluxes between Reco and GPP representing the net ecosystem exchange (NEE). NEE is measured mostly by either (often manual and seasonal) ground-level flux chambers or (automated and continuous) eddy covariance flux towers, where negative values of NEE indicate net C accumulation by the terrestrial ecosystem from the atmosphere (i.e., a C sink). Crucially, NECB calculations need to consider time scales, which need to capture fluctuations in climatic conditions and vegetation over time, the latter being especially important within managed systems, including recovery and regrowth periods. Moreover, complete estimates of NECB are rarely obtained, and it is often difficult to relate catchment-scale fluvial carbon losses to plot-level flux measurements of NEE and methane emissions.

Box 1. *Cont.*

Prescribed fire [16,18,21–23]:
Also known as controlled burning, managed burning, muirburn or prescribed burning. Prescribe fire is a management-ignited fire, i.e., the fire is applied and confined to a predefined area. It produces the fire behaviour and fire characteristics required to achieve management objectives. Prescribed fire in the British uplands is primarily carried out on grouse moors to promote favourable conditions for red grouse. Specifically, the aim is to provide a mosaic heather structure of tall, older stands for shelter, young stands with fresh, nutritious shoots for adults and short, open, recently managed stands containing a greater abundance of insect prey for chicks. Thus, every year, grouse moor managers burn multiple small patches of mature *C. vulgaris* to create a mosaic of differently aged patches across larger areas. However, Davies et al. [3] point out that "areas associated with burning tend to have greater *Calluna* cover, but managers do not distribute their effort randomly across landscapes and it is unclear if burning is the result or cause of increased *Calluna* cover." Where permitted, prescribed fire management in the British uplands is restricted to between 1 October–15 April (inclusive). The size and shape of individual burns are highly variable, but burns are usually no greater than 30 × 100 metres. Areas are re-burnt as soon as they become dominated by tall and 'leggy' *C. vulgaris*, which takes approximately 15 to >25 years but can be shorter or longer depending on the local climate affecting *Calluna* regrowth rates.

Spatiotemporal context:
The specific spatial and temporal extent over which a management intervention is applied, a measurement is taken or an estimate is applied.

Spheroidal carbonaceous particles (SCPs) [24]:
SCPs are a distinct form of black carbon produced when coal and oil are combusted at temperatures >1000 °C. They are deposited and preserved in peat layers, making them an excellent stratigraphic age/depth marker for recent time periods in the UK (i.e., starting with the onset of increased fossil fuel burning during the industrial revolution at around 1850 with a noticeable increase in SCP counts at around 1950 before reaching a peak around 1975).

Systematic review [25]:
An evidence synthesis approach with a clearly formulated question using explicit and systematic protocols to identify, select and critically appraise relevant research and collect and analyse data from the selected studies. Statistical methods (e.g., meta-analysis) may or may not be used to analyse and synthesise the results of the selected studies.

2. Comments on Gregg et al.'s Review Methodology

Firstly, Gregg et al. fail to describe their review protocols in any detail. For example, there is no information about how they searched for evidence, how evidence was assessed for inclusion, how evidence was synthesised or how evidence was critically appraised (i.e., how scientifically robust the evidence is). The little methodological information that is provided is ambiguous, such as when they state that they carried out a red, amber and green (RAG) assessment to determine the amount and agreement of evidence included for each review topic (red = low; amber = medium; green = high). However, they provide no detail about the thresholds used to determine when evidence fell into the red, amber and green categories.

Secondly, Gregg et al. state that they did not intend to conduct a systematic review. However, they should still have provided detailed protocols so that the strengths and weaknesses of their review could be assessed. Indeed, Gregg et al.'s review cannot be considered reliable without such detail and is, therefore, of little utility for land managers and policymakers [26–29]. Furthermore, failure to fully specify their protocols means that their review cannot be updated or compared to other reviews with divergent results [29]. These issues must be resolved as elsewhere Gregg et al. imply their review is comprehensive and robust by making statements such as "we conducted in-depth literature reviews across a range of habitats relevant to conservation in England . . . ", " . . . extensive peer-review . . . " and "using current scientific literature to provide a detailed overview of carbon sequestration cycling and storage in each of the habitats covered . . . ".

We cannot fully assess Greg et al.'s review approach until they provide additional detail. Nevertheless, the fact that they omitted key evidence suggests that their search protocols should have been more comprehensive. For example, the authors ignore the evidence on burning-induced charcoal inputs potentially increasing long-term carbon storage and reducing methane emissions within peatland ecosystems [30–34]. By omitting this evidence, Gregg et al. currently represents an incomplete and biased assessment that certainly did not "*reflect the current understanding in January 2021*" (p. 7). To address this and the issues outlined above, we recommend that the authors re-assess the evidence relating to carbon storage by habitat using a systematic review approach that follows the transparent and objective guidelines provided by the Collaboration for Environmental Evidence [25] or ROSES [35,36].

3. Misrepresentation of the Evidence

In this section, we highlight where Gregg et al. have misrepresented the evidence relating to prescribed fire impacts on blanket bog ecosystems and NECBs.

3.1. The Impact of Prescribed Fire on Blanket Bog

Gregg et al. claim, "There is increasing consensus in the scientific evidence that burning on blanket bog is damaging and having a detrimental impact on carbon stocks and sequestration rates" (p. 95).

Firstly, the scientific evidence about the impacts of prescribed fire on blanket bogs is equivocal: it can have a positive, negative or neutral impact depending on the ecological aspect being assessed and the spatiotemporal context under which it is examined [5,6,33,37–50]. This is no different to other widely accepted disturbance-based conservation interventions, such as grazing or mowing, which are damaging if employed too frequently, at the wrong scale or in the wrong area [51–55]. However, we do not generalise and say grazing or mowing are damaging overall because they are damaging in specific contexts (and vice versa). Moreover, initial and plot-level responses are likely to be negative due to vegetation removal. However, this would also be the case for alternative cutting, and it is the subsequent recovery phase to mature vegetation and the overall landscape-scale assessment rather than an individual plot-level assessment that best informs about ecological impacts. Prescribed fire is but one blanket bog vegetation management tool that may or may not be appropriate depending on site conditions and management aims [21].

Secondly, it is incorrect to state that prescribed burning has a detrimental impact on blanket bog carbon stocks and sequestration rates. To do so ignores the conflicting evidence [37,46,50,56] and the potential role of burning-induced charcoal within peatland carbon budgets [30,32,34,57,58]. More importantly, Gregg et al. fail to acknowledge that no study has conducted a comprehensive NECB assessment (i.e., an assessment of all NECB elements) across an entire burning management cycle (e.g., ~20 years). The Peatland-ES-UK project goes some way to address this crucial research gap using a randomised, multi-site, catchment-scale, Before-After-Control-Impact approach [59]. As of 2023, comprehensive NECB data has been collected for one-year pre-management (burning and mowing) and ten years post-management [59]. Once data collection reaches 20+ years (i.e., the documented management cycle for those sites), we will have a more realistic and accurate assessment of how prescribed burning influences blanket bog NECBs. However, the Peatland-ES-UK is but one study; additional and comprehensive NECB studies utilising a range of approaches are urgently required. Until then, the evidence base relating to burning impacts on blanket bog carbon budgets is dominated by studies that assess only part of the management cycle [33,50,60,61], lack significant NECB elements [33,50,60,61] or suffer from likely methodological issues [31], including a chronosequence study reporting (very unlikely) highest net C uptake one year after burning [61].

3.2. Prescribed Fire and Blanket Bog Climate Change Mitigation

"Healthy, functioning peatlands have a net cooling effect on the climate, locking up carbon and playing an important role in climate regulation ... However, England's peatlands have been severely degraded by management interventions such as drainage, burning and agricultural use, and now represent a net source of carbon and a warming effect ... There is increasing consensus in the scientific evidence that burning on blanket bog is damaging and having a detrimental impact on carbon stocks and sequestration rates." (p. 95).

Gregg et al. draw heavily on the evidence presented in the UK Peatlands Emissions Inventory [62] when assessing carbon storage and sequestration within blanket bogs. However, due to a paucity of data and issues of confounding between management interventions, the authors of the emissions inventory could not calculate separate emission factors for blanket bog subject to drainage or prescribed burning [62]. Therefore, we question how Gregg et al. can claim that prescribed burning will transform a blanket bog into a net source of greenhouse gases. The evidence on this topic is unclear [3,4,21], and no complete assessment is available [5,37,63].

"When in healthy condition they sequester carbon slowly but are unique in that they can go on doing so indefinitely" (p. v and p. 175).

Gregg et al. also imply that peat growth continues indefinitely at a substantial rate (see Figure 2 on p. 2). However, peat growth can be limited by site conditions and peatland age as well as by management such as drainage or peat cutting [37]. Accumulation is generally fastest when a peatland is young and wet (or when recovering from peat cutting [37]); if old, accumulation slows right down unless the climate becomes very wet and warm (as the net balance of carbon input versus decomposition changes over time and with climate) [64]. Thus, indefinite peat accumulation is most likely wrong as there will be a natural limit to peat formation (to some degree) based on the mass balance of the carbon gained versus the carbon being lost (most UK peatlands show an asymptotic depth increase [64]). Moreover, with increasing peat age/depth come associated risks (especially on slopes), including forming peat pipes and gully development (and erosion) and sudden mass loss events, such as bog bursts [15].

Finally, Gregg et al. omit key studies investigating fire-mediated impacts on important elements of the peatland NECB, such as the potential benefit of charcoal on long-term carbon storage [30,32,34,65] and the suppression of methane emissions via charcoal-mediated effects on microbes [31,33,57]. Moreover, the failure to manage fuel loads is another emerging issue that could lead to immense peatland carbon losses due to a catastrophic wildfire [15,46]. Notably, the risk of wildfires is predicted to increase considerably in the UK due to climate change [66]. Thus, when it comes to the future occurrence of wildfires on upland habitats such as blanket bog, "it's not if, but when" (Professor Rob Marrs, quoted in Barber-Lomax et al. [67]).

3.3. Rewetting, Prescribed Fire and Blanket Bog Wildfire Mitigation

"Baird and others (2019) note that degraded blanket bog sites are inherently a fire risk due to their combustible vegetation cover, while ecologically functioning peatlands with high-water tables and Sphagnum moss cover reduce the risk of deep burning by increasing the energy required to ignite peat and thereby restrict the burn depth ... Raising the water level and restoring peat forming vegetation is a more effective [than prescribed burning] way of managing these sites to reduce fire risk (Granath and others 2016; Glaves and others 2020)" (p. 115).

As far as we are aware, there is no available evidence comparing the relative wildfire mitigation potential of rewetting and prescribed burning on blanket bog. We are not questioning the ecological value of rewetting and revegetating bare and eroding peat; this is a clear conservation priority. Rather, by rewetting, we mean interventions in relation to wildfire mitigation on vegetated peatlands that raise the water table (e.g., ditch blocking or bunding), which are often implemented alongside planting *Sphagnum* plugs or spreading *Sphagnum* cuttings. The cited references of Baird et al. [68], Granath et al. [69] and Glaves et al. [70] certainly do not provide evidence that rewetting vegetated peatlands reduces wildfire risk. For example, Glaves et al. [70] is a review that cites Granath et al. [69] as the only evidence demonstrating the efficacy of rewetting in mitigating wildfire ignition. Baird et al. [68] is a comment paper containing only an opinion and no original research, but it also cites Granath et al. [69] to support the assertion that rewetting will reduce wildfire risk on blanket bog. However, Granath et al. [69] investigated the wildfire mitigation potential of rewetting lowland bogs subject to peat mining and deep drainage, which are not directly comparable to vegetated blanket bogs in the UK. More importantly, Granath et al. [69] do not compare the relative wildfire mitigation potential of rewetting and prescribed burning (or any combination thereof).

By increasing the energy required to ignite peat, rewetting may well mitigate wildfire ignition and damage within blanket bog ecosystems. However, near-saturated peat may still ignite and burn [71,72], and topographical and climatic limitations to the water balance (and the maximum water tables) mean we cannot expect rewetting everywhere to the same degree [64,73,74]. Thus, at any blanket bog site, we must consider a range of wildfire mitigation strategies, including prescribed burning. Determining the most appropriate wildfire mitigation interventions within UK ecosystems, including on blanket bog, is a clear priority for future research, as the devastation and huge emissions from recent UK peatland fires show [67,75,76].

3.4. Rewetting Is a 'No-Regrets' Option

"Raising water levels should be considered a 'no-regrets' option, in that benefits may be realised over longer periods as the peatland ecosystem adapts to wetter conditions (Evans and others 2018)" (p. 111). We currently lack the evidence to support such a generic statement. For example, and as mentioned above, rewetting may lead to increased methane emissions, especially when combined with increasing temperatures and or pH [63,77]. Note that methane has a much greater climate warming potential than carbon dioxide [78]. Moreover, note that the UK is projected to experience warmer summers alongside warmer and wetter winters [79]. Consequently, rewetting may lead to a scenario where the benefit of carbon captured and stored is reduced by or even less than the net emission contribution of the methane emitted, turning a blanket bog into a net source of greenhouse gas emissions.

The widescale rewetting of blanket bog could also potentially exacerbate flooding lower down the catchment (for a more in-depth discussion, see Ashby and Heinemeyer [6]—note we do not question the benefits of filling in drainage ditches or revegetation of bare peat). For example, rewetting aims to saturate peatland soils by raising the water table so that it is at or near the soil surface. While this process increases peat accumulation [80], heavy rain on a saturated blanket bog may lead to increased overland flow into headwater streams [81,82]. Blanket bog surface vegetation may slow overland flow during heavy rainfall [83]. However, it might not slow overland flow enough to reduce the speed and volume of water entering headwater streams. Worryingly, the flood mitigation potential of rewetted blanket bog (certainly in relation to ceasing burning management) seems to remain uncertain or unknown [84]. This evidence gap should ideally be addressed before large-scale blanket bog rewetting and (de)selective management approaches are implemented everywhere within flood-prone catchments, such as the upper River Calder (Hebden Bridge). Interestingly, dwarf shrub vegetation such as heather (*C. vulgaris*) has been shown to be slightly drier at the surface (likely due to higher evapotranspiration rates) [37,63]. Thus, dwarf shrubs may reduce overland flow by allowing additional storage during high-intensity rainfall events.

3.5. 'Peat-Forming' Species

Gregg et al. frequently refer to 'peat-forming' vegetation and state that, in the UK, *Sphagnum* species "*are the main contributors to peat formation in bogs*" (p. 99). The assumption that *Sphagnum* species are the primary 'peat-formers' within UK blanket bogs is not supported by any causal evidence [6]. Rather, it seems to be based on circumstantial evidence, such as greater quantities of *Sphagnum* fragments found within peat core sections subject to rapid peat growth [85,86]. However, there is a danger of circularity in this argument as it is difficult to determine if such periods of rapid peat growth are due to greater *Sphagnum* abundance or the presence of conditions favourable to peat formation and *Sphagnum* growth (e.g., high water tables and low pH). Furthermore, multiple UK studies have recorded the dominance of non-*Sphagnum* plant fragments within peat core sections encompassing periods of rapid peat growth [85–92]. In addition, more recent peat accumulation data suggest no clear link between *Sphagnum* abundance and peat accumulation [46,56,93].

Peat formation and accumulation are primarily driven by the presence of anoxic and acidic conditions, which are both predominantly promoted by high water tables [85]. In such conditions, the litter from any plant species will form peat, including *C. vulgaris* [64,85,86]. Nevertheless, by reducing soil pH and retaining water, *Sphagnum* species may enhance or maintain peat-forming conditions where water table depth is a limiting factor [94–97]. Similarly, by leaching phenolic compounds and slowing peat decomposition, woody species, such as *C. vulgaris*, can likely maintain peat-forming conditions as water tables drop [98].

We suggest the term 'peat-forming' ascribed to *Sphagnum* (and other species) be dropped until we have robust causal evidence about the relative peat-forming capabilities of different blanket bog plant species. We suggest 'peat-formation enhancing' or 'supporting' is a much better term to be used.

3.6. The History of Burning in the Uplands

Gregg et al. state, "Burning has been used as a tool in the English uplands for hundreds of years as a way of diversifying the age and structure of shrubs for game management and creating new growth for livestock grazing" (p. 113). It is implied that the current practice of prescribed burning carried out by grouse moor managers has only existed for the last ~200 years [99]. However, charcoal deposits in peat cores suggest that fire (wild or managed) has shaped the British uplands fairly frequently since the early Holocene [85,87,90,91,100–108]. Thus, burning has been a feature of the British uplands for thousands of years (e.g., ~6000 years [90,91]) and may well have contributed to the formation of blanket bog ecosystems [85,87,90,91,100–108]. Yet, we still do not fully understand the historical extent, frequency and ecological impact of prescribed fire or wildfire across the British uplands [106,108,109]. In our view, this is a crucial evidence gap that, if explored, would significantly inform upland management. Perhaps more importantly, such knowledge would also highlight the potential ecological utility of fire outside of promoting red grouse habitat. Indeed, grouse moor management is a contentious issue in the UK [2,110,111], and its synonymity with prescribed fire has been a significant obstacle to an informed and unbiased debate about the broader ecological role of fire in the British uplands [3,4].

3.7. Failure to Consider Methodological Flaws in the Evidence Base

Gregg et al. repeatedly cite evidence from studies with significant methodological flaws and/or no direct assessments of impacts on carbon storage but treat this evidence with equal validity as more scientifically robust studies. A case in point is this passage:

"In recent years the limitations of using single sites have been recognised and research into the impact of burning in the uplands has been commissioned on multi-catchment scales. The EMBER (Effects of Moorland Burning on the Ecohydrology of River basins) study was undertaken across 10 catchments split equally between burnt and unburnt in the Pennines. While the study did not look directly at the impact of burning on peatland carbon cycling, it did report that burning caused multiple negative environmental impacts that could be associated with the reduction in a peatland's potential to store or sequester carbon; such as lowered water tables, greater soil surface temperature extremes, loss of bog vegetation and peat-forming mosses and increases in water runoff (Brown and others 2014)" (p. 114).

The EMBER project was indeed a multi-catchment study across ten blanket peat catchments: five catchments subjected to prescribed burning and five unburnt 'control' catchments with no recent (>30 years) history of prescribed burning [112]. However, we assert that the results of the four peer-reviewed studies [113–116] published as part of the EMBER project should be treated with caution for the following reasons:

i. Unburnt and burnt treatment catchments were located within geographically separate and environmentally distinct sites, which meant 'site' was confounded with treatment [113–116];
ii. Environmental differences (i.e., confounding) between sites and treatments (burnt versus unburnt) were not (and due to the experimental design, cannot be) accounted for during statistical analysis [113–116];
iii. Data structure was not correctly accounted for during analysis, meaning each study used artificially inflated sample sizes (i.e., pseudoreplication). As such, the significance values reported are unreliable, likely too low and should not be used to generalise [117];
iv. Peat surface temperature results are suggestive of measurement error [7,8], and effect sizes remain unknown (but according to the published graphs [116], are likely to be small).

We have outlined, in detail, the methodological and statistical issues with the EMBER project [7,8], but others have pointed out related limitations in the experimental design [84]. Crucially, the EMBER authors failed to address these issues in their replies to our criticisms [9,10]. Gregg et al. should balance their reporting of the EMBER study by summarising both its strengths and limitations.

Gregg et al. also cite a study by Garnett et al. [56] which utilises the Hard Hill experiment at Moor House National Nature Reserve. This experiment consists of four 90 m × 60 m blocks (A–D), each divided into six 30 m × 30 m plots. Half of each block (three plots) was randomly assigned to exclude grazing using a post and wire fence, with the other half open to grazing all year round. Then, within each half, three burning treatments were randomly allocated: unburnt, burnt every 10 years and burnt every 20 years. All of the main experimental plots were burnt at the start of the experiment in 1954. Garnett et al. [56] only assessed C accumulation in three of the six experimental treatments: ungrazed and unburnt, grazed and unburnt, and grazed and burnt every ten years. However, the ten-year burning rotation was never applicable to Moor House, nor would it occur on most higher elevation blanket bog sites, which, due to slow *C. vulgaris* growth rates in the cold and wet upland climate, are managed using ~20–25 year burning rotations [118]. Therefore, the results of Garnett et al. [56] tell us little about the real-world impact of prescribed burning on blanket bog carbon dynamics. Indeed, whilst shorter rotations were encouraged as recently as the 1980s [119], modern burn rotations on blanket bogs are ~20–25 years [30,120,121]. Gregg et al. also fail to highlight potential methodological issues within Garnett et al. [56]. For example, the peat depth profiles do not show the expected SCP peak around 1975, and the reported charcoal layers do not agree with the oldest Hard Hill burn date of 1954 [30,122]. Furthermore, carbon content and bulk density data, both crucial aspects for the calculation of carbon accumulation rates, are based on questionable methods and assumptions and are not clearly reported on [30,60].

3.8. Misreporting of Heinemeyer et al. (2019)

Gregg et al. misreport the findings of Heinemeyer et al. [37]. For example, they state, "*The reported carbon values show that prior to the experimental management interventions all management groups (burnt, mowed, no intervention) acted as net carbon sources (though all had previously been subject to rotational burning). In the four years post-management, the carbon budget values indicate that burnt and mown treatments were net carbon sources*" (p. 114). However, it is important to note the following:

i. At the plot scale, the pre-management intervention values showed that all sites and treatments were carbon sinks, even when considering methane emissions. However, only after accounting for (very uncertain) fluvial carbon losses did two of the three study sites become net carbon sources (the wettest site remained a carbon sink) [37].
ii. Hardly any other study includes the level of detail measured by Heinemeyer et al. [37] (i.e., including all major NECB components), so a critical assessment and comparison of blanket bog carbon storage must consider the comparability and validity of the evidence presented by less detailed studies that omit key NECB elements.
iii. Since burning and mowing remove vegetation, it is obvious that burnt and mown plots will very likely be a net carbon source immediately after management (as vegetation needs to regrow to start sequestering carbon). Thus, any short-term findings are meaningless, which is why the project was anticipated and set up to be long-term. Indeed, the project specification written by Defra, Natural England and the peer-review process recommended that any such study must consider the slow responses and recovery to management and incorporate the regrowth of managed vegetation to maturity [37]. As the peer-review comments indicated, at least 25 years are needed to obtain meaningful and policy-relevant data (i.e., data that covers the entire management cycle).

In addition, in Table 4.1 (p. 97), in their first publication of NERR094, Gregg et al. incorrectly reported data from Heinemeyer et al. [37]. According to Table 2 in Heinemeyer et al. [37], blanket bog soil carbon ranges from 354–619 t C ha^{-1}, with a mid-point of about 500 t C ha^{-1}. In Table 4.1, Gregg et al. reported values of 353–954 t C ha^{-1}, with a mid-point of 799 t C ha^{-1}. Gregg et al. used data related to the plot rather than the catchment scale (cf. Table 2 in Heinemeyer et al. [37]). We are grateful that Gregg et al. recently updated Table 4.1 and used the catchment scale data as it is more representative. However, Gregg et al. could have also estimated vegetation carbon data in Table 4.1 using the blanket bog biomass data provided by Heinemeyer et al. [37] and others (e.g., Santana et al. [123]). Finally, in Table 4.5 (p. 109), Gregg et al. reproduce peat carbon stock values from Heinemeyer et al. [37], but the values reported were also inappropriate (they were also corrected in a recent edition—stated as 'minor corrections'—in response to an e-mail exchange between A. Heinemeyer and the review's authors). The lead author of Heinemeyer et al. [37] would be more than happy to further liaise with Gregg et al. to discuss the Peatland-ES-UK findings and the constraints in interpreting its short-term (4-year post management) findings, which severely limit its value in inferring general management impacts (i.e., requiring monitoring a full management cycle) as shown in changes over the subsequent 5 years [63].

4. Recommendations

We recommend Gregg et al. make the following revisions to enhance the value of their review for academics, land managers and policymakers:

➢ Clearly describe the review methodology so the robustness and utility of the review can be assessed.
➢ If the described review methodology indicates Gregg et al.'s approach is subject to high levels of bias (e.g., [29]), we recommend that they re-assess the evidence using a systematic approach that follows explicit and objective guidelines (e.g., [25,35,36]).
➢ Remove unevidenced statements or clearly state that such statements are conjecture. This is important because Gregg et al. is a review, and readers may confuse conjecture with fact.
➢ We would also suggest including a balanced set of peer-reviewers; to only include a representative of the RSPB (Royal Society of the Protection of Birds)—an organisation with strong views opposing grouse moor management and rotational burning of heather—seems biased.

We would like to end with three quotes from Davies et al. [3] who stated the following:

i. *"In the absence of sound evidence and consensus, it is vital that managers and scientists adopt an 'adaptive' approach to decision making."*

ii. *"Our objective should be to use fire as one tool in management that aims to produce structurally diverse upland landscapes that protect a range of ecosystem functions."*
iii. *"Such assessments need to focus on the landscape scale and on elucidating trends over the entire fire rotation rather than just looking at the short-term outcomes of single burns that are a pulse disturbance with obvious negative outcomes for particular metrics."*

We think that since the publication of their paper, a growing evidence base has only increased to support their argument of including prescribed fire as a valuable and potentially beneficial management tool on heather-dominated peatlands. This should be conducted in a careful and unbiased approach and be based on sound assessments of the evidence base, considering limitations in methods and analyses alongside published evidence.

Author Contributions: Both authors conceived and contributed equally to the writing of the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: No specific funding was received for the writing and submission of this manuscript. However, A.H. was supported by Internal Publication funding from the Stockholm Environment Institute, The University of York's Policy Engine (TYPE) support funds and received research funding before and/or during the writing of this manuscript from various organisations and funders (Natural Environmental Research Council (NE/X005143/1); Yorkshire Water Services; United Utilities; Moorland Association; British Association for Shooting and Conservation; The Heather Trust (with funding from the HD Wills Trust); Law Family Charitable Foundation) and the Ecological Continuity Trust. M.A.A. was not supported by any funding during the writing and submission of this manuscript.

Conflicts of Interest: A.H. was supported by internal publication funding from the Stockholm Environment Institute, The University of York's Policy Engine (TYPE) support funds and received research funding before and/or during the writing of this manuscript from various organisations and funders (Natural Environmental Research Council; Yorkshire Water Services; United Utilities; Moorland Association; British Association for Shooting and Conservation; The Heather Trust (with funding from the HD Wills Trust); Law Family Charitable Foundation) and the Ecological Continuity Trust. M.A.A. previously provided ecological consulting services to the Moorland Association (April 2019–March 2021) and the Game & Wildlife Conservation Trust (October 2019–March 2021).

References

1. Gregg, R.; Elias, J.L.; Alonso, I.; Crosher, I.E.; Muto, P.; Morecroft, M.D. *Carbon Storage and Sequestration by Habitat: A Review of the Evidence*, 2nd ed.; Natural England Report NERR094; Natural England: York, UK, 2021.
2. Avery, M. *Inglorious: Conflict in the Uplands*; Bloomsbury Publishing: London, UK, 2015.
3. Davies, G.M.; Kettridge, N.; Stoof, C.R.; Gray, A.; Ascoli, D.; Fernandes, P.M.; Marrs, R.; Allen, K.A.; Doerr, S.H.; Clay, G.D.; et al. The Role of Fire in UK Peatland and Moorland Management: The Need for Informed, Unbiased Debate. *Philos. Trans. R. Soc. B Biol. Sci.* **2016**, *371*, 20150342. [CrossRef]
4. Davies, G.M.; Kettridge, N.; Stoof, C.R.; Gray, A.; Marrs, R.; Ascoli, D.; Fernandes, P.M.; Allen, K.A.; Doerr, S.H.; Clay, G.D.; et al. Informed Debate on the Use of Fire for Peatland Management Means Acknowledging the Complexity of Socio-Ecological Systems. *Nat. Conserv.* **2016**, *16*, 59–77. [CrossRef]
5. Harper, A.R.; Doerr, S.H.; Santin, C.; Froyd, C.A.; Sinnadurai, P. Prescribed Fire and Its Impacts on Ecosystem Services in the UK. *Sci. Total Environ.* **2018**, *624*, 691–703. [CrossRef] [PubMed]
6. Ashby, M.A.; Heinemeyer, A. A Critical Review of the IUCN UK Peatland Programme's "Burning and Peatlands" Position Statement. *Wetlands* **2021**, *41*, 56. [CrossRef]
7. Ashby, M.A.; Heinemeyer, A. Prescribed Burning Impacts on Ecosystem Services in the British Uplands: A Methodological Critique of the EMBER Project. *J. Appl. Ecol.* **2019**, *57*, 2112–2120. [CrossRef]
8. Ashby, M.A.; Heinemeyer, A. Whither Scientific Debate? A Rebuttal of "Contextualising UK Moorland Burning Studies: Geographical versus Potential Sponsorship-Bias Effects on Research Conclusions" by Brown and Holden. *bioRxiv* **2019**, 731117. [CrossRef]
9. Brown, L.; Holden, J. Contextualising UK Moorland Burning Studies: Geographical versus Potential Sponsorship-Bias Effects on Research Conclusions. *bioRxiv* **2019**, 731117. [CrossRef]
10. Brown, L.E.; Holden, J. Contextualizing UK Moorland Burning Studies with Geographical Variables and Sponsor Identity. *J. Appl. Ecol.* **2020**, *57*, 2121–2131. [CrossRef]
11. Francos, M.; Úbeda, X. Prescribed Fire Management. *Curr. Opin. Environ. Sci. Health* **2021**, *21*, 100250. [CrossRef]
12. Hunter, M.E.; Robles, M.D. Tamm Review: The Effects of Prescribed Fire on Wildfire Regimes and Impacts: A Framework for Comparison. *For. Ecol. Manag.* **2020**, *475*, 118435. [CrossRef]

13. Volkova, L.; Roxburgh, S.H.; Weston, C.J. Effects of Prescribed Fire Frequency on Wildfire Emissions and Carbon Sequestration in a Fire Adapted Ecosystem Using a Comprehensive Carbon Model. *J. Environ. Manag.* **2021**, *290*, 112673. [CrossRef]
14. JNCC. *UK Biodiversity Action Plan—Priority Habitat Descriptions*; Joint Nature Conservation Committee: Peterborough, UK, 2011.
15. Lindsay, R. *Peatbogs and Carbon: A Critical Synthesis to Inform Policy Development in Oceanic Peat Bog Conservation and Restoration in the Context of Climate Change*; Environmental Research Group, University of East London: London, UK, 2010.
16. Palmer, S.C.F.; Bacon, P.J. The Utilization of Heather Moorland by Territorial Red Grouse Lagopus Lagopus Scoticus. *Ibis* **2001**, *143*, 222–232. [CrossRef]
17. Tharme, A.P.; Green, R.E.; Baines, D.; Bainbridge, I.P.; O'Brien, M. The Effect of Management for Red Grouse Shooting on the Population Density of Breeding Birds on Heather-Dominated Moorland. *J. Appl. Ecol.* **2001**, *38*, 439–457. [CrossRef]
18. GWCT. *Your Essential Guide to Grouse Shooting and Moorland Management*; Game & Wildlife Conservation Trust: Fordingbridge, UK, 2017.
19. Walker, M.; Johnsen, S.; Rasmussen, S.O.; Popp, T.; Steffensen, J.-P.; Gibbard, P.; Hoek, W.; Lowe, J.; Andrews, J.; Björck, S.; et al. Formal Definition and Dating of the GSSP (Global Stratotype Section and Point) for the Base of the Holocene Using the Greenland NGRIP Ice Core, and Selected Auxiliary Records. *J. Quat. Sci.* **2009**, *24*, 3–17. [CrossRef]
20. Chapin, F.S.; Woodwell, G.M.; Randerson, J.T.; Rastetter, E.B.; Lovett, G.M.; Baldocchi, D.D.; Clark, D.A.; Harmon, M.E.; Schimel, D.S.; Valentini, R.; et al. Reconciling Carbon-Cycle Concepts, Terminology, and Methods. *Ecosystems* **2006**, *9*, 1041–1050. [CrossRef]
21. Davies, M.G.; Gray, A.; Hamilton, A.; Legg, C.J. The Future of Fire Management in the British Uplands. *Int. J. Biodivers. Sci. Manag.* **2008**, *4*, 127–147. [CrossRef]
22. Buchanan, G.; Grant, M.; Sanderson, R.; Pearce-Higgins, J. The Contribution of Invertebrate Taxa to Moorland Bird Diets and the Potential Implications of Land-Use Management. *Ibis* **2006**, *148*, 615–628. [CrossRef]
23. The Heather and Grass Etc. Burning (England) Regulations. 2021. Available online: https://www.legislation.gov.uk/uksi/2021/158/contents/made (accessed on 5 May 2023).
24. Swindles, G.T.; Watson, E.; Turner, T.E.; Galloway, J.M.; Hadlari, T.; Wheeler, J.; Bacon, K.L. Spheroidal Carbonaceous Particles Are a Defining Stratigraphic Marker for the Anthropocene. *Sci. Rep.* **2015**, *5*, 10264. [CrossRef]
25. Collaboration for Environmental Evidence. *Guidelines and Standards for Evidence Synthesis in Environmental Management: Version 5.0*; Pullin, A.S., Frampton, G.K., Livoreil, B., Petrokofsky, G., Eds.; Collaboration for Environmental Evidence: Online, 2018; Online only document of the CEE, a UK Charity No. 1157607; Available online: https://environmentalevidence.org/information-for-authors/ (accessed on 5 May 2023).
26. Pussegoda, K.; Turner, L.; Garritty, C.; Mayhew, A.; Skidmore, B.; Stevens, A.; Boutron, I.; Sarkis-Onofre, R.; Bjerre, L.M.; Hróbjartsson, A.; et al. Systematic Review Adherence to Methodological or Reporting Quality. *Syst. Rev.* **2017**, *6*, 131. [CrossRef]
27. O'Leary, B.C.; Kvist, K.; Bayliss, H.R.; Derroire, G.; Healey, J.R.; Hughes, K.; Kleinschroth, F.; Sciberras, M.; Woodcock, P.; Pullin, A.S. The Reliability of Evidence Review Methodology in Environmental Science and Conservation. *Environ. Sci. Policy* **2016**, *64*, 75–82. [CrossRef]
28. Haddaway, N.R.; Macura, B. The Role of Reporting Standards in Producing Robust Literature Reviews. *Nat. Clim. Chang.* **2018**, *8*, 444–447. [CrossRef]
29. Haddaway, N.R.; Bethel, A.; Dicks, L.V.; Koricheva, J.; Macura, B.; Petrokofsky, G.; Pullin, A.S.; Savilaakso, S.; Stewart, G.B. Eight Problems with Literature Reviews and How to Fix Them. *Nat. Ecol. Evol.* **2020**, *4*, 1582–1589. [CrossRef] [PubMed]
30. Heinemeyer, A.; Asena, Q.; Burn, W.L.; Jones, A.L. Peatland Carbon Stocks and Burn History: Blanket Bog Peat Core Evidence Highlights Charcoal Impacts on Peat Physical Properties and Long-Term Carbon Storage. *Geo Geogr. Environ.* **2018**, *5*, e00063. [CrossRef]
31. Davidson, S.J.; Van Beest, C.; Petrone, R.; Strack, M. Wildfire Overrides Hydrological Controls on Boreal Peatland Methane Emissions. *Biogeosciences* **2019**, *16*, 2651–2660. [CrossRef]
32. Leifeld, J.; Alewell, C.; Bader, C.; Krüger, J.P.; Mueller, C.W.; Sommer, M.; Steffens, M.; Szidat, S. Pyrogenic Carbon Contributes Substantially to Carbon Storage in Intact and Degraded Northern Peatlands. *Land Degrad. Dev.* **2018**, *29*, 2082–2091. [CrossRef]
33. Gray, A.; Davies, G.M.; Domènech, R.; Taylor, E.; Levy, P.E. Peatland Wildfire Severity and Post-Fire Gaseous Carbon Fluxes. *Ecosystems* **2021**, *24*, 713–725. [CrossRef]
34. Flanagan, N.E.; Wang, H.; Winton, S.; Richardson, C.J. Low-Severity Fire as a Mechanism of Organic Matter Protection in Global Peatlands: Thermal Alteration Slows Decomposition. *Glob. Chang. Biol.* **2020**, *26*, 3930–3946. [CrossRef]
35. Haddaway, N.R.; Macura, B.; Whaley, P.; Pullin, A.S. ROSES for Systematic Map Protocols. Version 1.0. 2017. Online only Document. Available online: https://www.roses-reporting.com/systematic-map-protocols (accessed on 5 May 2023).
36. Haddaway, N.R.; Macura, B.; Whaley, P.; Pullin, A.S. ROSES RepOrting Standards for Systematic Evidence Syntheses: Pro Forma, Flow-Diagram and Descriptive Summary of the Plan and Conduct of Environmental Systematic Reviews and Systematic Maps. *Environ. Evid.* **2018**, *7*, 7. [CrossRef]

37. Heinemeyer, A.; Vallack, H.; Morton, P.; Pateman, R.; Dytham, C.; Ineson, P.; McClean, C.; Bristow, C.; Pearce-Higgins, J. *Restoration of Heather-Dominated Blanket Bog Vegetation on Grouse Moors for Biodiversity, Carbon Storage, Greenhouse Gas Emissions and Water Regulation: Comparing Burning to Alternative Mowing and Uncut Management. Final Report to Defra on Project BD5104*; Stockholm Environment Institute at the University of York: York, UK, 2019. Available online: https://sciencesearch.defra.gov.uk/ProjectDetails?ProjectId=17733 (accessed on 5 May 2023).
38. Whitehead, S.; Weald, H.; Baines, D. Post-Burning Responses by Vegetation on Blanket Bog Peatland Sites on a Scottish Grouse Moor. *Ecol. Indic.* **2021**, *123*, 107336. [CrossRef]
39. Whitehead, S.C.; Baines, D. Moorland Vegetation Responses Following Prescribed Burning on Blanket Peat. *Int. J. Wildland Fire* **2018**, *27*, 658–664. [CrossRef]
40. Milligan, G.; Rose, R.J.; O'Reilly, J.; Marrs, R.H. Effects of Rotational Prescribed Burning and Sheep Grazing on Moorland Plant Communities: Results from a 60-Year Intervention Experiment. *Land Degrad. Dev.* **2018**, *29*, 1397–1412. [CrossRef]
41. Noble, A.; Crowle, A.; Glaves, D.J.; Palmer, S.M.; Holden, J. Fire Temperatures and Sphagnum Damage during Prescribed Burning on Peatlands. *Ecol. Indic.* **2019**, *103*, 471–478. [CrossRef]
42. Noble, A.; O'Reilly, J.; Glaves, D.J.; Crowle, A.; Palmer, S.M.; Holden, J. Impacts of Prescribed Burning on Sphagnum Mosses in a Long-Term Peatland Field Experiment. *PLoS ONE* **2018**, *13*, e0206320. [CrossRef]
43. Noble, A.; Palmer, S.M.; Glaves, D.J.; Crowle, A.; Holden, J. Impacts of Peat Bulk Density, Ash Deposition and Rainwater Chemistry on Establishment of Peatland Mosses. *Plant Soil* **2017**, *419*, 41–52. [CrossRef]
44. Noble, A.; Palmer, S.M.; Glaves, D.J.; Crowle, A.; Holden, J. Peatland Vegetation Change and Establishment of Re-Introduced Sphagnum Moss after Prescribed Burning. *Biodivers. Conserv.* **2019**, *28*, 939–952. [CrossRef]
45. Noble, A.; Palmer, S.M.; Glaves, D.J.; Crowle, A.; Brown, L.E.; Holden, J. Prescribed Burning, Atmospheric Pollution and Grazing Effects on Peatland Vegetation Composition. *J. Appl. Ecol.* **2018**, *55*, 559–569. [CrossRef]
46. Marrs, R.H.; Marsland, E.-L.; Lingard, R.; Appleby, P.G.; Piliposyan, G.T.; Rose, R.J.; O'Reilly, J.; Milligan, G.; Allen, K.A.; Alday, J.G.; et al. Experimental Evidence for Sustained Carbon Sequestration in Fire-Managed, Peat Moorlands. *Nat. Geosci.* **2019**, *12*, 108–112. [CrossRef]
47. Grau-Andrés, R.; Davies, G.M.; Gray, A.; Scott, E.M.; Waldron, S. Fire Severity Is More Sensitive to Low Fuel Moisture Content on Calluna Heathlands than on Peat Bogs. *Sci. Total Environ.* **2018**, *616–617*, 1261–1269. [CrossRef]
48. Grau-Andrés, R.; Davies, G.M.; Waldron, S.; Scott, E.M.; Gray, A. Increased Fire Severity Alters Initial Vegetation Regeneration across Calluna-Dominated Ecosystems. *J. Environ. Manag.* **2019**, *231*, 1004–1011. [CrossRef]
49. Grau-Andrés, R.; Gray, A.; Davies, G.M. Sphagnum Abundance and Photosynthetic Capacity Show Rapid Short-Term Recovery Following Managed Burning. *Plant Ecol. Divers.* **2017**, *10*, 353–359. [CrossRef]
50. Grau-Andrés, R.; Gray, A.; Davies, G.M.; Scott, E.M.; Waldron, S. Burning Increases Post-Fire Carbon Emissions in a Heathland and a Raised Bog, but Experimental Manipulation of Fire Severity Has No Effect. *J. Environ. Manag.* **2019**, *233*, 321–328. [CrossRef] [PubMed]
51. Tälle, M.; Deák, B.; Poschlod, P.; Valkó, O.; Westerberg, L.; Milberg, P. Similar Effects of Different Mowing Frequencies on the Conservation Value of Semi-Natural Grasslands in Europe. *Biodivers. Conserv.* **2018**, *27*, 2451–2475. [CrossRef]
52. Tälle, M.; Deák, B.; Poschlod, P.; Valkó, O.; Westerberg, L.; Milberg, P. Grazing vs. Mowing: A Meta-Analysis of Biodiversity Benefits for Grassland Management. *Agric. Ecosyst. Environ.* **2016**, *222*, 200–212. [CrossRef]
53. Török, P.; Penksza, K.; Tóth, E.; Kelemen, A.; Sonkoly, J.; Tóthmérész, B. Vegetation Type and Grazing Intensity Jointly Shape Grazing Effects on Grassland Biodiversity. *Ecol. Evol.* **2018**, *8*, 10326–10335. [CrossRef]
54. Wang, C.; Tang, Y. A Global Meta-Analyses of the Response of Multi-Taxa Diversity to Grazing Intensity in Grasslands. *Environ. Res. Lett.* **2019**, *14*, 114003. [CrossRef]
55. Sutherland, W.; Dicks, L.; Petrovan, S.; Smith, R. *What Works in Conservation 2021*; Open Book Publishers: Cambridge, UK, 2021.
56. Garnett, M.H.; Ineson, P.; Stevenson, A.C. Effects of Burning and Grazing on Carbon Sequestration in a Pennine Blanket Bog, UK. *Holocene* **2000**, *10*, 729–736. [CrossRef]
57. Sun, T.; Guzman, J.J.L.; Seward, J.D.; Enders, A.; Yavitt, J.B.; Lehmann, J.; Angenent, L.T. Suppressing Peatland Methane Production by Electron Snorkeling through Pyrogenic Carbon in Controlled Laboratory Incubations. *Nat. Commun.* **2021**, *12*, 4119. [CrossRef]
58. Jones, M.W.; Santín, C.; van der Werf, G.R.; Doerr, S.H. Global Fire Emissions Buffered by the Production of Pyrogenic Carbon. *Nat. Geosci.* **2019**, *12*, 742–747. [CrossRef]
59. Heinemeyer, A. Welcome to: Peatland-ES-UK. Available online: https://peatland-es-uk.york.ac.uk/ (accessed on 5 May 2023).
60. Clay, G.D.; Worrall, F.; Rose, R. Carbon Budgets of an Upland Blanket Bog Managed by Prescribed Fire. *J. Geophys. Res. Biogeosci.* **2010**, *115*, G04037. [CrossRef]
61. Clay, G.D.; Worrall, F.; Aebischer, N.J. Carbon Stocks and Carbon Fluxes from a 10-Year Prescribed Burning Chronosequence on a UK Blanket Peat. *Soil Use Manag.* **2015**, *31*, 39–51. [CrossRef]
62. Evans, C.; Artz, R.; Moxley, J.; Smyth, M.-A.; Taylor, E.; Archer, E.; Burden, A.; Williamson, J.; Donnelly, D.; Thomson, A.; et al. *Implementation of an Emission Inventory for UK Peatlands*; Report to the Department for Business, Energy and Industrial Strategy; Centre for Ecology and Hydrology: Bangor, UK, 2017; p. 88.

63. Heinemeyer, A.; David, T.; Pateman, R. *Restoration of Heather-Dominated Blanket Bog Vegetation for Biodiversity, Carbon Storage, Greenhouse Gas Emissions and Water Regulation: Comparing Burning to Alternative Mowing and Uncut Management: Final 10-Year Report to the Project Advisory Group of Peatland-ES-UK. Research Report*; Stockholm Environment Institute at the University of York: York, UK, 2023.
64. Heinemeyer, A.; Croft, S.; Garnett, M.H.; Gloor, E.; Holden, J.; Lomas, M.R.; Ineson, P. The MILLENNIA Peat Cohort Model: Predicting Past, Present and Future Soil Carbon Budgets and Fluxes under Changing Climates in Peatlands. *Clim. Res.* **2010**, *45*, 207–226. [CrossRef]
65. Santín, C.; Doerr, S.H.; Preston, C.M.; González-Rodríguez, G. Pyrogenic Organic Matter Production from Wildfires: A Missing Sink in the Global Carbon Cycle. *Glob. Chang. Biol.* **2015**, *21*, 1621–1633. [CrossRef]
66. Albertson, K.; Aylen, J.; Cavan, G.; McMorrow, J. Climate Change and the Future Occurrence of Moorland Wildfires in the Peak District of the UK. *Clim. Res.* **2010**, *45*, 105–118. [CrossRef]
67. Barber-Lomax, A.; Battye, R.; Gibson, S.; Castellnou, M.; Bachfischer, M. *Peak District National Park Wildfire Risk Assessment*; Peak District National Park Wildfire Risk Assessment Steering Group: Peak District, UK, 2022.
68. Baird, A.J.; Evans, C.D.; Mills, R.; Morris, P.J.; Page, S.E.; Peacock, M.; Reed, M.; Robroek, B.J.M.; Stoneman, R.; Swindles, G.T.; et al. Validity of Managing Peatlands with Fire. *Nat. Geosci.* **2019**, *12*, 884–885. [CrossRef]
69. Granath, G.; Moore, P.A.; Lukenbach, M.C.; Waddington, J.M. Mitigating Wildfire Carbon Loss in Managed Northern Peatlands through Restoration. *Sci. Rep.* **2016**, *6*, 28498. [CrossRef]
70. Glaves, D.; Crowle, A.; Bruemmer, C.; Lenaghan, S. *The Causes and Prevention of Wildfire on Heathlands and Peatlands in England (NEER014)*; Natural England: Peterborough, UK, 2020.
71. Lin, S.; Sun, P.; Huang, X. Can Peat Soil Support a Flaming Wildfire? *Int. J. Wildland Fire* **2019**, *28*, 601–613. [CrossRef]
72. Huang, X.; Rein, G. Downward Spread of Smouldering Peat Fire: The Role of Moisture, Density and Oxygen Supply. *Int. J. Wildland Fire* **2017**, *26*, 907–918. [CrossRef]
73. Gallego-Sala, A.V.; Colin Prentice, I. Blanket Peat Biome Endangered by Climate Change. *Nat. Clim. Chang.* **2013**, *3*, 152–155. [CrossRef]
74. Gallego-Sala, A.V.; Clark, J.M.; House, J.I.; Orr, H.G.; Prentice, I.C.; Smith, P.; Farewell, T.; Chapman, S.J. Bioclimatic Envelope Model of Climate Change Impacts on Blanket Peatland Distribution in Great Britain. *Clim. Res.* **2010**, *45*, 151–162. [CrossRef]
75. Belcher, C.; Brown, I.; Clay, G.; Doerr, S.; Elliott, A.; Gazzard, R.; Kettridge, N.; Morison, J.; Perry, M.; Santin, C.; et al. *UK Wildfires and Their Climate Challenges. Expert Led Report Prepared for the Third Climate Chang. Risk Assessment*; Global Systems Institute, University of Exeter: Exeter, UK, 2021.
76. Graham, A.M.; Pope, R.J.; McQuaid, J.B.; Pringle, K.P.; Arnold, S.R.; Bruno, A.G.; Moore, D.P.; Harrison, J.J.; Chipperfield, M.P.; Rigby, R.; et al. Impact of the June 2018 Saddleworth Moor Wildfires on Air Quality in Northern England. *Environ. Res. Commun.* **2020**, *2*, 031001. [CrossRef]
77. Abdalla, M.; Hastings, A.; Truu, J.; Espenberg, M.; Mander, Ü.; Smith, P. Emissions of Methane from Northern Peatlands: A Review of Management Impacts and Implications for Future Management Options. *Ecol. Evol.* **2016**, *6*, 7080–7102. [CrossRef] [PubMed]
78. Balcombe, P.; Speirs, J.F.; Brandon, N.P.; Hawkes, A.D. Methane Emissions: Choosing the Right Climate Metric and Time Horizon. *Environ. Sci. Process. Impacts* **2018**, *20*, 1323–1339. [CrossRef] [PubMed]
79. Kendon, M.; McCarthy, M.; Jevrejeva, S.; Matthews, A.; Sparks, T.; Garforth, J.; Kennedy, J. State of the UK Climate 2021. *Int. J. Climatol.* **2022**, *42* (Suppl. S1), 1–80. [CrossRef]
80. Leifeld, J.; Menichetti, L. The Underappreciated Potential of Peatlands in Global Climate Change Mitigation Strategies. *Nat. Commun.* **2018**, *9*, 1071. [CrossRef] [PubMed]
81. Holden, J.; Burt, T.P. Runoff Production in Blanket Peat Covered Catchments. *Water Resour. Res.* **2003**, *39*, 1191. [CrossRef]
82. Acreman, M.; Holden, J. How Wetlands Affect Floods. *Wetlands* **2013**, *33*, 773–786. [CrossRef]
83. Holden, J.; Kirkby, M.J.; Lane, S.N.; Milledge, D.G.; Brookes, C.J.; Holden, V.; McDonald, A.T. Overland Flow Velocity and Roughness Properties in Peatlands. *Water Resour. Res.* **2008**, *44*, W06415. [CrossRef]
84. Allott, T.; Auñón, J.; Dunn, C.; Evans, M.; Labadz, J.; Lunt, P.; MacDonald, M.; Nisbet, T.; Owen, R.; Pilkington, M.; et al. *Peatland Catchments and Natural Flood Management*; IUCN UK Peatland Programme: Edinburgh, UK, 2019.
85. Gillingham, P.; Stewart, J.; Binney, H. *The Historic Peat Record: Implications for the Restoration of Blanket Bog. Natural England, Evidence Review NEER011*; Natural England: Peterborough, UK, 2016.
86. Shepherd, M.; Labadz, J.; Caporn, S.; Crowle, A.; Goodison, R.; Rebane, M.; Waters, R. *Restoration of Degraded Blanket Bog. Natural England Evidence Review NEER003*; Natural England: Peterborough, UK, 2013.
87. Fyfe, R.M.; Woodbridge, J. Differences in Time and Space in Vegetation Patterning: Analysis of Pollen Data from Dartmoor, UK. *Landsc. Ecol.* **2012**, *27*, 745–760. [CrossRef]
88. Fyfe, R.M.; Brown, A.G.; Rippon, S.J. Mid- to Late-Holocene Vegetation History of Greater Exmoor, UK: Estimating the Spatial Extent of Human-Induced Vegetation Change. *Veg. Hist. Archaeobotany* **2003**, *12*, 215–232. [CrossRef]
89. Fyfe, R.M.; Ombashi, H.; Davies, H.J.; Head, K. Quantified Moorland Vegetation and Assessment of the Role of Burning over the Past Five Millennia. *J. Veg. Sci.* **2018**, *29*, 393–403. [CrossRef]
90. McCarroll, J.; Chambers, F.M.; Webb, J.C.; Thom, T. Application of Palaeoecology for Peatland Conservation at Mossdale Moor, UK. *Quat. Int.* **2017**, *432*, 39–47. [CrossRef]

91. Webb, J.C.; McCarroll, J.; Chambers, F.M.; Thom, T. Evidence for the Little Ice Age in Upland Northwestern Europe: Multiproxy Climate Data from Three Blanket Mires in Northern England. *Holocene* **2022**, *32*, 451–467. [CrossRef]
92. Chambers, F.; Crowle, A.; Daniell, J.; Mauquoy, D.; McCarroll, J.; Sanderson, N.; Thom, T.; Toms, P.; Webb, J. Ascertaining the Nature and Timing of Mire Degradation: Using Palaeoecology to Assist Future Conservation Management in Northern England. *AIMS Environ. Sci.* **2017**, *4*, 54–82. [CrossRef]
93. Piilo, S.R.; Zhang, H.; Garneau, M.; Gallego-Sala, A.; Amesbury, M.J.; Väliranta, M.M. Recent Peat and Carbon Accumulation Following the Little Ice Age in Northwestern Québec, Canada. *Environ. Res. Lett.* **2019**, *14*, 075002. [CrossRef]
94. Clymo, R.S.; Kramer, J.R.; Hammerton, D.; Beament, J.W.L.; Bradshaw, A.D.; Chester, P.F.; Holdgate, M.W.; Sugden, T.M.; Thrush, B.A. Sphagnum-Dominated Peat Bog: A Naturally Acid Ecosystem. *Philos. Trans. R. Soc. London. B Biol. Sci.* **1984**, *305*, 487–499. [CrossRef]
95. Bacon, K.L.; Baird, A.J.; Blundell, A.; Bourgault, M.-A.; Chapman, P.J.; Dargie, G.; Dooling, G.P.; Gee, C.; Holden, J.; Kelly, T.J.; et al. Questioning Ten Common Assumptions about Peatlands. *Mires Peat* **2017**, *19*, 1–23.
96. Gorham, E. The Development of Peat Lands. *Q. Rev. Biol.* **1957**, *32*, 145–166. [CrossRef]
97. van Breemen, N. How Sphagnum Bogs down Other Plants. *Trends Ecol. Evol.* **1995**, *10*, 270–275. [CrossRef]
98. Fenner, N.; Freeman, C. Woody Litter Protects Peat Carbon Stocks during Drought. *Nat. Clim. Chang.* **2020**, *10*, 363–369. [CrossRef]
99. Simmons, I. *The Moorlands of England and Wales an Environmental History, 8000 BC–AD 2000*; Edinburgh University Press: Edinburgh, UK, 2003.
100. Simmons, I.; Tooley, M. *The Environment in British Prehistory*; Duckworth: London, UK, 1981.
101. Moore, J. Forest Fire and Human Interaction in the Early Holocene Woodlands of Britain. *Palaeogeogr. Palaeoclim. Palaeoecol.* **2000**, *164*, 125–137. [CrossRef]
102. Caseldine, C.; Hatton, J. The Development of High Moorland on Dartmoor: Fire and the Influence of Mesolithic Activity on Vegetation Change. In *Climate Change and Human Impact on the Landscape: Studies in Palaeoecology and Environmental Archaeology*; Chambers, F.M., Ed.; Springer: Dordrecht, The Netherlands, 1993; pp. 119–131. [CrossRef]
103. Innes, J.B.; Blackford, J.J. The Ecology of Late Mesolithic Woodland Disturbances: Model Testing with Fungal Spore Assemblage Data. *J. Archaeol. Sci.* **2003**, *30*, 185–194. [CrossRef]
104. Froyd, C.A. Holocene Fire in the Scottish Highlands: Evidence from Macroscopic Charcoal Records. *Holocene* **2006**, *16*, 235–249. [CrossRef]
105. Dodgshon, R.A.; Olsson, G.A. Heather Moorland in the Scottish Highlands: The History of a Cultural Landscape, 1600–1880. *J. Hist. Geogr.* **2006**, *32*, 21–37. [CrossRef]
106. Tsakiridou, M.; Hardiman, M.; Grant, M.J.; Lincoln, P.C.; Cunningham, L. Evidence of Wildfire in the British Isles during the Last Glacial-Interglacial Transition: Revealing Spatiotemporal Patterns and Controls. *Proc. Geol. Assoc.* **2020**, *131*, 562–577. [CrossRef]
107. Innes, J.; Blackford, J.; Simmons, I. Woodland Disturbance and Possible Land-Use Regimes during the Late Mesolithic in the English Uplands: Pollen, Charcoal and Non-Pollen Palynomorph Evidence from Bluewath Beck, North York Moors, UK. *Veg. Hist. Archaeobotany* **2010**, *19*, 439–452. [CrossRef]
108. Jacobi, R.M.; Tallis, J.H.; Mellars, P.A. The Southern Pennine Mesolithic and the Ecological Record. *J. Archaeol. Sci.* **1976**, *3*, 307–320. [CrossRef]
109. Radley, J. Significance of Major Moorland Fires. *Nature* **1965**, *205*, 1254–1259. [CrossRef]
110. Sotherton, N.; Baines, D.; Aebischer, N.J. An Alternative View of Moorland Management for Red Grouse Lagopus Lagopus Scotica. *Ibis* **2017**, *159*, 693–698. [CrossRef]
111. Thompson, P.S.; Douglas, D.J.T.; Hoccom, D.G.; Knott, J.; Roos, S.; Wilson, J.D. Environmental Impacts of High-Output Driven Shooting of Red Grouse Lagopus Lagopus Scotica. *Ibis* **2016**, *158*, 446–452. [CrossRef]
112. Brown, L.; Holden, J.; Palmer, S. *Effects of Moorland Burning on the Ecohydrology of River Basins. Key Findings from the EMBER Project*; University of Leeds: Leeds, UK, 2014.
113. Holden, J.; Palmer, S.M.; Johnston, K.; Wearing, C.; Irvine, B.; Brown, L.E. Impact of Prescribed Burning on Blanket Peat Hydrology. *Water Resour. Res.* **2015**, *51*, 6472–6484. [CrossRef]
114. Holden, J.; Wearing, C.; Palmer, S.; Jackson, B.; Johnston, K.; Brown, L.E. Fire Decreases Near-Surface Hydraulic Conductivity and Macropore Flow in Blanket Peat. *Hydrol. Process.* **2014**, *28*, 2868–2876. [CrossRef]
115. Brown, L.E.; Johnston, K.; Palmer, S.M.; Aspray, K.L.; Holden, J. River Ecosystem Response to Prescribed Vegetation Burning on Blanket Peatland. *PLoS ONE* **2013**, *8*, e81023. [CrossRef]
116. Brown, L.E.; Palmer, S.M.; Johnston, K.; Holden, J. Vegetation Management with Fire Modifies Peatland Soil Thermal Regime. *J. Environ. Manag.* **2015**, *154*, 166–176. [CrossRef]
117. Davies, G.M.; Gray, A. Don't Let Spurious Accusations of Pseudoreplication Limit Our Ability to Learn from Natural Experiments (and Other Messy Kinds of Ecological Monitoring). *Ecol. Evol.* **2015**, *5*, 5295–5304. [CrossRef]
118. Alday, J.G.; Santana, V.M.; Lee, H.; Allen, K.A.; Marrs, R.H. Above-Ground Biomass Accumulation Patterns in Moorlands after Prescribed Burning and Low-Intensity Grazing. *Perspect. Plant Ecol. Evol. Syst.* **2015**, *17*, 388–396. [CrossRef]
119. Yallop, A.R.; Thacker, J.I.; Thomas, G.; Stephens, M.; Clutterbuck, B.; Brewer, T.; Sannier, C.A.D. The Extent and Intensity of Management Burning in the English Uplands. *J. Appl. Ecol.* **2006**, *43*, 1138–1148. [CrossRef]
120. Thacker, J.I.; Yallop, A.R.; Clutterbuck, B. *Burning in the English Uplands—A Review, Reconciliation and Comparison of Results of Natural England's Burn Monitoring: 2005–2014 (IPENS055)*; Natural England: Peterborough, UK, 2014.

121. Lees, K.J.; Buxton, J.; Boulton, C.A.; Abrams, J.F.; Lenton, T.M. Using Satellite Data to Assess Management Frequency and Rate of Regeneration on Heather Moorlands in England as a Resilience Indicator. *Environ. Res. Commun.* **2021**, *3*, 085003. [CrossRef]
122. Heinemeyer, A.; Burn, W.L.; Asena, Q.; Jones, A.L.; Ashby, M.A. Response to: Comment on "Peatland Carbon Stocks and Burn History: Blanket Bog Peat Core Evidence Highlights Charcoal Impacts on Peat Physical Properties and Long-Term Carbon Storage" by Evans et al. (Geo: Geography and Environment 2019; E00075). *Geo Geogr. Environ.* **2019**, *6*, e00078. [CrossRef]
123. Santana, V.M.; Alday, J.G.; Lee, H.; Allen, K.A.; Marrs, R.H. Modelling Carbon Emissions in Calluna Vulgaris–Dominated Ecosystems When Prescribed Burning and Wildfires Interact. *PLoS ONE* **2016**, *11*, e0167137. [CrossRef]