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COMMENTARY

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Prescribed burning impacts on ecosystem services in the British uplands: A methodological critique of the EMBER project

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Abstract

1. Due to its novelty and scale, the EMBER project is a key study within the prescribed burning evidence base. However, it has several significant but overlooked methodological flaws.
2. In this paper, we outline and discuss these flaws. In doing so, we aim to highlight the current paucity of evidence relating to prescribed burning impacts on ecosystem services within the British uplands.
3. We show that the results of the EMBER project are currently unreliable because: it used a correlative space-for-time approach; treatments were located within geographically separate and environmentally distinct sites; environmental differences between sites and treatments were not accounted for during statistical analysis; and, peat surface temperature results are suggestive of measurement error.
4. *Policy Implications*. Given the importance of the EMBER project, our findings suggest that (a) government agencies and policymakers need to re-examine the strengths and limitations of the prescribed burning evidence base; and, (b) future work needs to control for site-specific differences so that prescribed burning impacts on ecosystem services can be reliably identified.

KEYWORDS
ecosystem services, evidence-based policy, experimental design, prescribed rotational burning, the EMBER project, upland habitats, upland land management

1 | INTRODUCTION

In recent years, researchers have begun to highlight the limited evidence surrounding prescribed burning impacts on ecosystem services within the British uplands (Davies et al., 2016; Glaves et al., 2013; Harper, Doerr, Santin, Froyd, & Sinnadurai, 2018). The EMBER project (Effects of Moorland Burning on the Ecohydrology of River basins) aimed to address part of this knowledge gap by conducting the most extensive study thus far on the ecosystem effects of prescribed rotational burning (Brown, Holden, & Palmer, 2014). However, we believe that this study suffers from a series of important but overlooked methodological flaws. Our objective in this paper is to describe and discuss these flaws. In doing so, we aim to stimulate a broader debate about the current evidence linking prescribed burning with the degradation of upland ecosystems and the ecosystem services they provide. We fully acknowledge that every scientific study (including ours) is limited by practical considerations such as time and cost. Nevertheless, such practical considerations should not preclude a study from being critically assessed to provide a more nuanced view of the evidence base and encourage improvements to study design and data analysis. Furthermore, a thorough examination of the evidence is particularly important in applied ecology where the implementation of the results will have practical, economic and policy-related consequences.

2 | THE EMBER CRITIQUE

2.1 | Background

The EMBER project aimed to improve our current understanding about the effects of prescribed rotational burning on water quality, hydrology, aquatic biodiversity and soil properties within upland peat-dominated river catchments (Brown et al., 2014). It did this over five years using five burnt and five unburnt river catchments with a total of 120 soil plots located within the English Pennines (ibid). Both its novelty and its scale make it an important study within the prescribed burning evidence base.

Overall, results from the EMBER project suggest that prescribed burning on blanket bog has clear negative effects on aquatic invertebrates, river water quality, peat hydrology, peat chemistry, peat structure and peat surface temperatures (Brown et al., 2014). Unsurprisingly, these findings meant that the project received a lot of positive media attention upon its release in 2014 (see, for example, Amos, 2014; Avery, 2014; Bawden, 2014; Webster, 2014). However, we assert that the findings of the EMBER study are currently unreliable because: it used a correlative space-for-time (SfT) approach; treatments were located within geographically separate and environmentally distinct sites; environmental differences between sites and treatments were not accounted for during statistical analysis; and, peat surface temperature results are suggestive of additional methodological inaccuracies.

Our critique uses the methodological information provided by four peer-reviewed research studies relating to parts 3–6 of the main EMBER report (Table 1). It is worth noting that, depending on the response variable investigated, the EMBER study used different combinations of study catchments and soil plots (Table 1). Additional information about the EMBER experimental design is given within Appendix S1, which also contains a detailed description of data sources, collection methods and statistical analysis for the data presented and discussed in the following sections.

2.2 | Correlative space-for-time approach

The EMBER project used a correlative SfT approach whereby comparisons were made between unburnt controls and burnt treatments (and between a chronosequence of different burn ages) well after burning had taken place (Brown et al., 2014). This approach is a cheaper and quicker alternative to conducting controlled field experiments. However, SfT studies assume that control and treatment plots had similar pre-disturbance conditions, which is unlikely to be true due to the environmental heterogeneity of most ecosystems (Johnson & Miyanishi, 2008; Pickett, 1989). Consequently, the results of SfT studies are not as reliable or accurate as those produced through controlled experimentation (França et al., 2016).

2.3 | Geographical and topographic separation of treatments

The authors of the EMBER project chose to locate treatments (unburnt and burnt catchments + soil plots) within geographically separate sites (Figure 1). This study design assumes that sites are similar in every respect except for burning management (cf. Schwarz, 2014a, 2014b). We believe that this assumption is flawed because each study site differed in one or more of the following environmental variables: mean monthly temperature (°C), mean monthly rainfall (mm), elevation (m), underlying geology and vegetation communities (Table 2 and 3 and Appendix S1). Many of these variables are known to affect the ecohydrology of upland river basins (e.g. Simmons, 2003; Durance & Ormerod, 2007; Yallop, Clutterbuck, & Thacker, 2010; Armstrong, Holden, Luxton, & Quinton, 2012; Ritson et al., 2014; Armstrong, Waldron, Ostle, Richardson, & Whitaker, 2015; Parry et al., 2015; Bell et al., 2018). For example, Armstrong et al. (2012) found that peatland vegetation type effects dissolved organic carbon (DOC) levels within soil and drain water samples. Moreover, elevation exerts a strong influence on precipitation, which, in turn, effects peatland water tables and overland flow (Heinemeyer et al., 2010).

Plot and catchment specific data also indicate that there were environmental differences between treatments (Figures 2–6). These data are highlighted below and grouped by study focus using the different catchment and soil plot combinations adopted by Brown, Johnston, Palmer, Aspray, and Holden (2013), Holden et al. (2014), Brown, Palmer, Johnston, and Holden (2015) and Holden et al. (2015).

2.3.1 | Streams within all five burnt catchments versus streams within all five unburnt catchments

This approach was used to investigate burning impacts on aquatic invertebrate communities, stream ecosystem functioning, water quality (Brown et al., 2013) and streamflow (Holden et al., 2015) (Table 1). The five burnt catchments are significantly drier than the five unburnt catchments (Figure 2b). Burnt catchments were also smaller, at lower elevations and warmer, although these differences were not statistically significant (Figure 2a, c and d).

2.3.2 | Burnt versus unburnt plots across all ten catchments

Holden et al. (2015) used this experimental set up to investigate burning impacts on water table depth. Unburnt plots were at significantly greater elevations and on significantly steeper slopes (Figure 3a and b). Also, a higher proportion of unburnt plots had a northerly aspect (Figure 4a).

TABLE 1 Summary of the peer-reviewed articles associated with the EMBER project (Brown et al., 2014)

Authors	Related chapter	Response variables	Experimental set-up and analysis
Brown et al. (2013)	Chp 6	Aquatic biodiversity, stream ecosystem functioning and water quality	Compared streams in five burnt catchments to streams in five unburnt catchments. The fact that unburnt and burnt streams were in separate sites **was not accounted for during statistical analysis**.
Holden et al. (2014)	Chp 3 & 4	Peat near-surface infiltration and macropore flow	Compared plots of different burn ages within the Bull Clough catchment (burnt 2 years, 4 years and > 15 years prior to the study) to unburnt plots within the Moss Burn catchment, as well as plots affected by a recent wildfire (<1-year-old) in the Oakner Clough catchment. Three 400 m^2 plots were used for each burning treatment. These were positioned in top, middle and bottom hillslope positions. The fact that unburnt, burnt and recent wildfire plots were in separate sites **was not accounted for during statistical analysis**.
Brown et al. (2015)	Chp 5	Peat temperature	Compared plots of different burn ages within the Bull Clough catchment (burnt < 2 years, 3–4 years, 5–7 years and 15–25 years prior to the study) to unburnt plots within the Oakner Clough catchment. Three 400 m^2 plots were used for each burning treatment, positioned in top, middle and bottom hillslope positions. The fact that unburnt and burnt plots were in separate sites **was not accounted for during statistical analysis.**
Holden et al. (2015)	Chp 4	Water table depth, overland flow and streamflow	This study compared (response variables in parentheses): 1. Streams in five burnt catchments to streams in five unburnt catchments (streamflow). 2. 60 burnt and 60 unburnt 400 m^2 plots across all ten catchments. Within each catchment, three plots were positioned in low, mid and high slope positions (water table depth). 3. Plots of different burn ages in the five burnt catchments to plots within the five unburnt catchments. The burn age treatments were < 2 years, 3–4 years, 5–7 years and > 10 since burning. Within each burnt catchment there were three 400 m^2 plots per burn age with one of these corresponding to low, mid or high slope positions. Within each unburnt catchment, three 400 m^2 plots were positioned in low, mid and high slope positions (water table depth). 4. Plots of different burn ages within the Bull Clough catchment (burnt < 2 years, 3–4 years, 5–7 years and 15–25 years prior to the study) to unburnt plots within the Oakner Clough catchment. Three 400 m^2 plots were used for each burning treatment. These were positioned in top, middle and bottom hillslope positions (overland flow and water table depth). The fact that unburnt and burnt streams and plots were within separate sites **was not accounted for during statistical analysis**.

2.3.3 | Burnt plots of different burn ages versus unburnt plots across all ten catchments

Plots of different burn ages (ranging from <2 years to >10 years) were compared with each other and with unburnt plots by Holden et al. (2015) while investigating burning impacts on water table depth. Plots of different burn ages were at similar elevations to each other but at lower elevations than unburnt plots; however, this pattern was not significant (Figure 3c). Conversely, slope angle varied between plots of different burn ages and unburnt plots, but again, this pattern was not significant, yet it showed a clear trend (Figure 3d). The proportion of plots with a northerly aspect also varied between plots of different burn ages and unburnt plots (Figure 4b). Again, this pattern showed a clear trend and was most pronounced when comparing unburnt plots with burnt plots that were <2 years old (B2) (Figure 4b).

2.3.4 | Burnt plots of different burn ages within Bull Clough versus unburnt plots within Moss Burn versus wildfire plots within Oakner Clough

This approach was used by Holden et al. (2014) to examine the impact of burning on peat near-surface infiltration and macropore flow. Plots of different burn ages were positioned at a similar elevation to each other but a lower elevation than unburnt plots and a higher elevation than wildfire plots (Figure 5a). In terms of between treatment differences in slope angle: wildfire plots were located on steeper slopes than all treatments except for burnt plots that were >15 years old (B15+); B15+ plots were located on steeper slopes than B2 plots and plots that were 3–4 years old (B4); B4 plots were located on steeper slopes than B2 plots; and, the slope angle of unburnt plots varied considerably but was shallower than wildfire plots (Figure 5b).

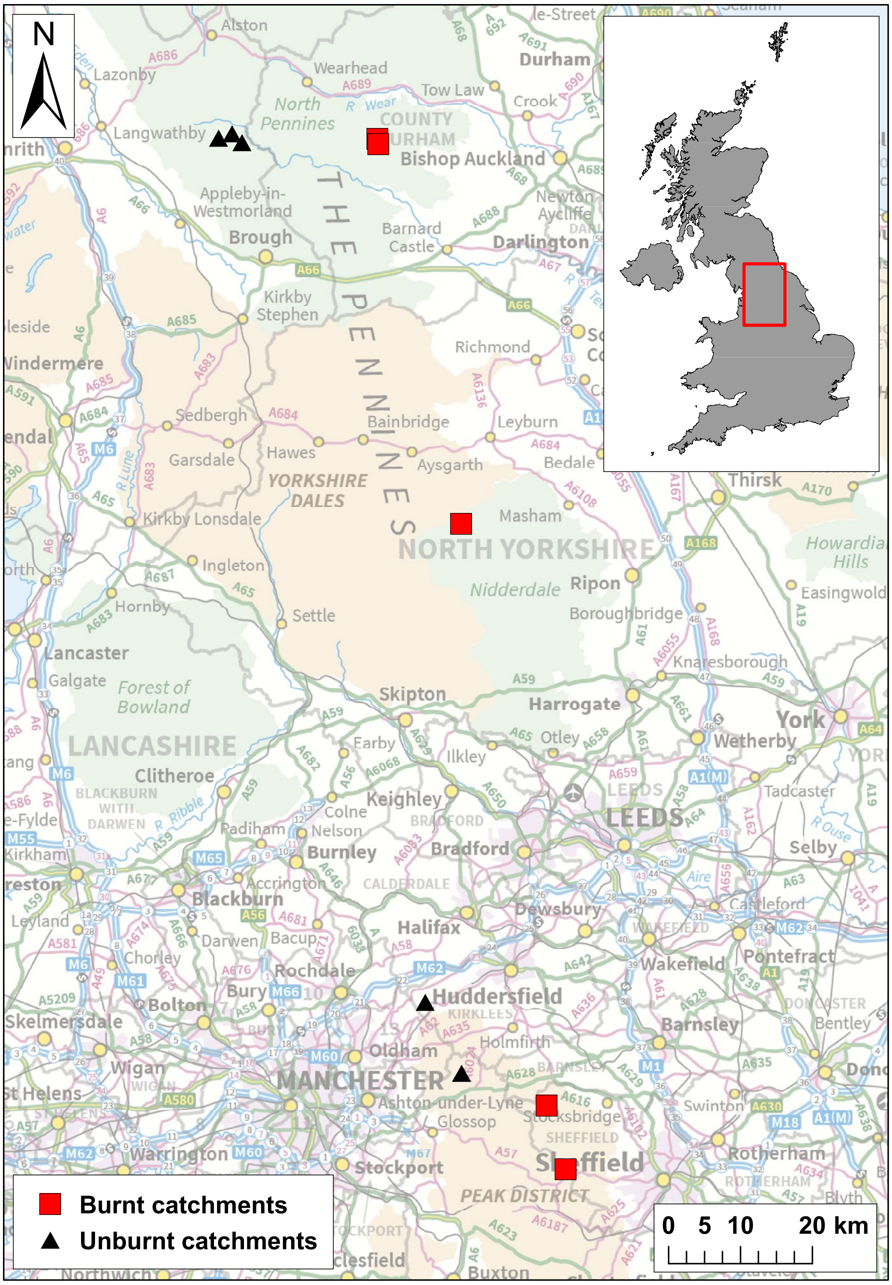

FIGURE 1 Map showing the locations of the five burnt (red squares) and five unburnt (black triangles) EMBER catchments. The Ordnance Survey MiniScale basemap TIFF (version 01/2018) was downloaded on the 30th October 2018 from https://www.ordnancesurvey.co.uk/opendatadownload/products.html

2.3.5 | Burnt plots of different burn ages within Bull Clough versus unburnt plots within Oakner Clough

This approach was used to investigate prescribed burning impacts on peat temperature (Brown et al., 2015), water table depth and overland flow (Holden et al., 2015). Plots of different burn ages were positioned at a similar elevation to each other but a higher elevation than unburnt plots (Figure 6a). Unburnt plots and B15+ plots had similar slope angles, but both these treatments were located on steeper slopes than B2 and B4 plots, and plots that were 5–7 years old (B7) (Figure 6b). B2 and B7 plots also had similar slope angles but were located on shallower slopes than B4 plots.

2.4 | Statistical inaccuracies

When analysing ecological field data, there are usually multiple covariates acting upon a response variable in addition to the predictor variable of interest (Schwarz, 2014a; Zuur, Ieno, & Smith, 2007). If covariates are known and measured, they can be dealt with to some extent by including them as variables during data analysis: this partitions the variation in the dataset accounted for by the covariate(s) so that the effect of the predictor variable can be examined in isolation (Pourhoseingholi, Baghestani, & Vahedi, 2012; Zuur, Ieno, Walker, Saveliev, & Smith, 2009). Failure to include a covariate can produce misleading results (Gail, Wieand, & Piantadosi, 1984). Furthermore,

TABLE 2 Locations and environmental conditions of the five burnt and five unburnt EMBER catchments. Location information was taken from Brown et al. (2014). Catchment environmental data were obtained from a variety of sources which are described in Table S1.2 within Appendix S1

Management/catchment	Location	British grid reference	Monthly temperature (°C)	Monthly rainfall (mm)	Elevation (m)	Area (km^2)	Geology
Burnt catchments							
Bull Clough	Midhope Moor, Peak District	SK1915897463	6.33	123.56	498.0	0.7	Carboniferous and Jurassic sandstone
Rising Clough	Derwent Moors, Peak District	SK2180288624	7.63	97.93	415.5	1.8	Carboniferous gritstone and sandstone
Woo Gill	Nidderdale, Yorkshire Dales	SE0723278444	7.14	112.94	488.0	1.0	Carboniferous and Jurassic mudstone
Great Eggleshope beck	Teesdale, North Pennines	NY9558732021	5.39	99.95	566.5	1.6	Carboniferous mudstone, sandstone and limestone
Lodgegill Sike	Teesdale, North Pennines	NY9572631276	5.39	99.95	561.5	1.2	Carboniferous mudstone, sandstone and limestone
Unburnt catchments							
Crowden Little Beck	Longendale, South Pennines	SE0728701970	6.77	130.60	468.5	3.1	Carboniferous gritstone and sandstone
Green Burn	Teesdale, North Pennines	NY7674331473	5.46	147.29	641.0	0.7	Carboniferous sandstone, limestone and shale
Moss Burn	Teesdale, North Pennines	NY7535632708	5.46	147.29	664.0	1.4	Carboniferous sandstone, limestone and shale
Oakner Clough	Marsden Moor, South Pennines	SE0224111836	7.71	117.11	345.5	1.2	Carboniferous gritstone and sandstone
Trout Beck	Teesdale, North Pennines	NY7348532097	4.38	120.37	694.5	2.8	Carboniferous sandstone, limestone and shale

TABLE 3 The dominant national vegetation classification (NVC) types and plant species found within burnt and unburnt EMBER study catchments. This information is taken from Hedley (2013), Holden et al. (2015) and Noble et al. (2018)

Management/site	NVC type	Dominant plant species
Burnt catchments		
Bull Clough	H9b	*Calluna vulgaris*, *Eriophorum* spp., *Rubus chamaemorus*, *Vaccinium myrtillus*
Rising Clough	H9b	*Calluna vulgaris*, *Eriophorum* spp., *Campylopus introflexus*
Woo Gill	M19a	*Calluna vulgaris*, *Eriophorum* spp., *Campylopus*, *Hypnum jutlandicum*, *Vaccinium myrtillus*
Great Eggleshope beck	M19a	*Calluna vulgaris*, *Eriophorum* spp., *Campylopus*, *Hypnum jutlandicum*, *Vaccinium myrtillus*, *Sphagnum capillifolium*
Lodgegill Sike	M19a	*Calluna vulgaris*, *Hypnum jutlandicum*, *Polytrichum commune*
Unburnt catchments		
Crowden Little Beck	M20b	*Vaccinium myrtillus*, *Empetrum nigrum*, *Eriophorum* spp., *Deschampsia flexuosa*
Green Burn	M19b	*Empetrum nigrum*, *Eriophorum vaginatum*, *Hypnum jutlandicum*, *Plagiothecium undulatum*, *Pleurozium schreberi*, *Rhytidiadelphus loreus*, *Sphagnum capillifolium*
Moss Burn	M19b	*Calluna vulgaris*, *Empetrum nigrum*, *Eriophorum vaginatum*, *Hypnum jutlandicum*, *Pleurozium schreberi*, *Sphagnum capillifolium*
Oakner Clough	M20b	*Eriophorum* spp., *Molinia caerulea*
Trout Beck	M19b	*Calluna vulgaris*, *Eriophorum vaginatum*, *Hypnum jutlandicum*, *Plagiothecium undulatum*, *Pleurozium schreberi*, *Rhytidiadelphus loreus*

researchers conducting multi-site ecological field studies where treatment replicates are located within each site should include 'site' and/or any known environmental factors as covariates during data analysis; since, even though sites may appear similar, they are highly likely to be different in some unknown way, and these unknown differences may influence the results (Schwarz, 2014a). Such site level effects are likely to exert a greater influence on the results of ecological field studies where treatments are within separate sites. In such cases, it is even more important to control for known site differences during data analysis.

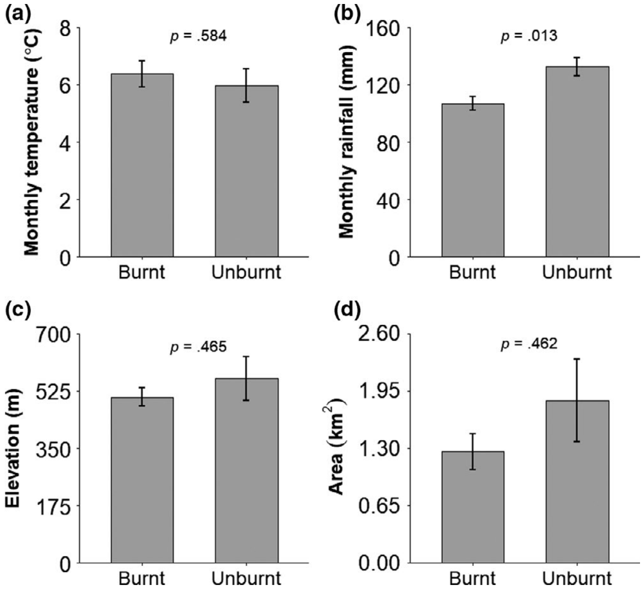

FIGURE 2 The environmental and physical differences between the five burnt and five unburnt EMBER study catchments. Showing the mean (± *SEM*) differences in (a) monthly temperature, (b) monthly rainfall, (c) elevation and (d) area. *p*-values are from one-way ANOVA (a & b) or Kruskal–Wallis rank sum tests (c & d)

As discussed above, the burnt and unburnt treatments within the EMBER study were located within separate sites, and both sites

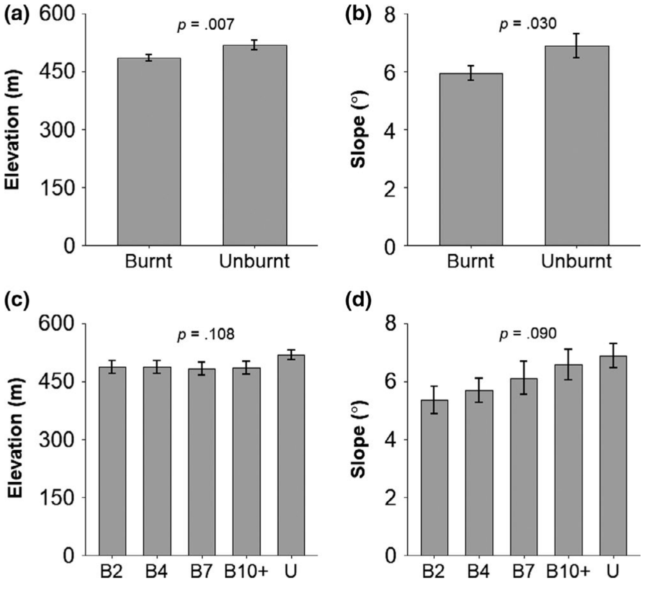

FIGURE 3 The topographical differences between the EMBER treatment plots. Showing the mean (± *SEM*) differences in (a) elevation and (b) slope values of the burnt (n = 60) and unburnt (n = 60) EMBER study plots. Also shown are the mean (± *SEM*) differences in (c) elevation and (d) slope values for the same plots when they are grouped by burn age treatment: 'B2' = <2 years old (n = 15), 'B4' = 3–4 years old (n = 15), 'B7' = 5–7 years old (n = 15), 'B10+' = >10 years old (n = 15) and 'U' = unburnt (n = 60). *p*-values are from Kruskal–Wallis rank sum tests

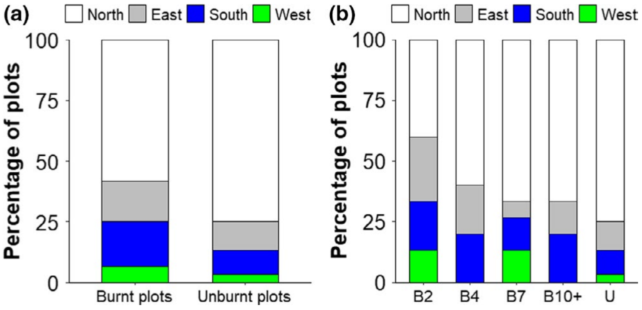

FIGURE 4 The different aspects of the EMBER treatment plots. (a) Showing the percentage of burnt (*n* = 60) and unburnt (*n* = 60) EMBER plots with a north (N, NE, NW), east (E), south (S, SE, SW) or west (W) facing aspect. (b) Showing the percentage of plots of different burn ages with a north, east, south or west facing aspect: 'B2' = <2 years old (*n* = 15), 'B4' = 3–4 years old (*n* = 15), 'B7' = 5–7 years old (*n* = 15), 'B10+' = >10 years old (*n* = 15) and 'U' = unburnt (*n* = 60)

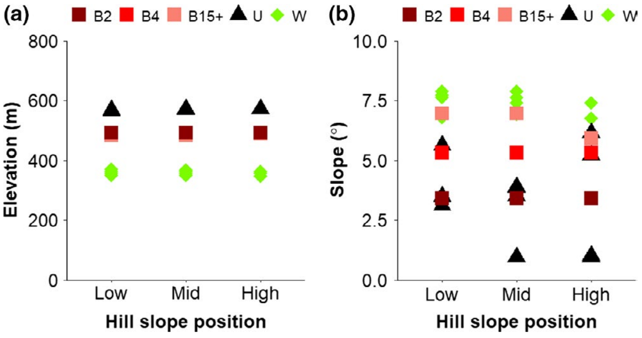

FIGURE 5 The topographical differences between the sub-set of EMBER treatment plots used by Holden et al. (2014). (a) Showing the elevation values for: 'B2' (<2 years old; *n* = 3), 'B4' (3–4 years old; *n* = 3) and 'B15+' (>15 years old; *n* = 3) plots within the Bull Clough study catchment; 'U' (unburnt; *n* = 12) plots within the Moss Burn study catchment; and, 'W' (recent wildfire; *n* = 12) plots within the Oakner Clough study catchment; values are grouped along the *x*-axis by plot slope position: low, medium and high. (b) Showing the slope values for: B2, B4 and B15+ plots within the Bull Clough study catchment; unburnt (U) plots within the Moss Burn study catchment; and, recent wildfire (W) plots within the Oakner Clough study catchment; values are grouped along the *x*-axis by plot slope position: low, medium and high

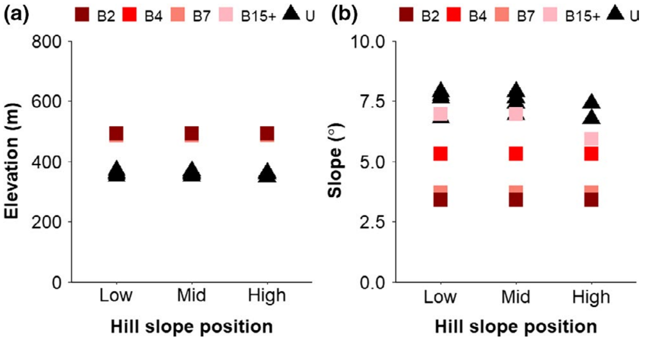

FIGURE 6 The topographical differences between the sub-set of EMBER treatment plots used by Brown et al. (2015) and Holden et al. (2015). (a) Showing the elevation values for: 'B2' (<2 years old; *n* = 3), 'B4' (3–4 years old; *n* = 3), 'B7' (5–7 years old; *n* = 3) and 'B15+' (>15 years old; *n* = 3) plots within the Bull Clough study catchment; and, 'U' (unburnt; *n* = 12) plots within the Oakner Clough study catchment; values are grouped along the *x*-axis by plot slope position: low, medium and high. (b) Showing the slope values for B2, B4, B7 and B15+ plots within the Bull Clough study catchment; and, unburnt (U) plots within the Oakner Clough study catchment; values are grouped along the *x*-axis by plot slope position: low, medium and high

and treatment plots differed in a range of key environmental variables that are likely to have influenced the results (e.g. elevation, rainfall, temperature, slope, aspect and vegetation composition). However, to our surprise, none of the peer-reviewed articles part of the main EMBER report attempted to control for any of these site/treatment differences during data analysis (Table 1). Interestingly, Brown et al. (2013) state that '*Differences between individual rivers* (i.e. sites) *were not assessed with MANOVA as the main focus of the study was on management effects*.' We believe that this statistical approach is flawed and, combined with the choice to locate treatments in separate and environmentally distinct sites, means that the results reported by the EMBER project cannot robustly be attributed to burning management. Perhaps the EMBER authors did not control for site effects because they found it had no bearing on the results. If so, then they should have stated this and ideally provided some supporting analyses.

In contrast, while not associated with the main EMBER project, Noble et al. (2018) did control for site when they examined the effect of several environmental variables (including burning management) on the cover of different plant species within the EMBER study plots. They state that '*Site was included in all models* (generalized linear mixed models) *as a random effect to account for grouping of plots within sites*' (ibid).

2.5 | Peat temperature measurements

Brown et al. (2015) used Gemini PB-5001 thermistors to measure how vegetation removal through burning influences peat temperature. This type of thermistor has a long metal external sensor that will artificially heat up if any part (but mostly the tip) is exposed to the sun. Exposure to the sun can result in large short-term temperature spikes (see graphs in Appendix 1 of Heinemeyer et al., forthcoming[1]). Brown et al. (2015) report extremely high maximum peat surface (0–1 cm) temperatures (up to 52.8°C) within burnt plots of different ages. The relatively low occurrence of these maxima events (cf. Figure 2 in Brown et al., 2015) suggests that the thermistor sensor was periodically exposed to the sun and that the temperatures recorded were, therefore, artificially high.

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[1] This is the previously Defra-funded (BD5104) and now extended Peatland-ES-UK project. A report presenting the results from the first five years is currently pending final approval by Defra and is anticipated to be published in September 2019.

3 | CONCLUSIONS

The EMBER project is currently the only published multi-site study to examine the effects of burning on multiple ecosystem processes at both the plot and catchment level (but see, Heinemeyer et al., forthcoming[1]). Consequently, it is likely to have had a strong influence on environmental policy and land management decisions. However, we have demonstrated that the results of the EMBER project should be treated with considerable caution due to a series of statistical inadequacies and what appear to be several important methodological flaws. These findings suggest that: (a) policymakers need to re-examine the strengths and limitations of the prescribed burning evidence base; and, (b) researchers need to fully account for potential site-specific differences in any future work so that prescribed burning impacts on ecosystem services can be reliably identified.

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AUTHORS' CONTRIBUTIONS

M.A.A. and A.H. conceived the paper; M.A.A. collected and analysed the data and wrote the first draft of the manuscript. Both M.A.A. and A.H. interpreted the results, revised the manuscript and gave final approval for publication.

DATA AVAILABILITY STATEMENT

EMBER plot location data are available via the University of Leeds respository https://doi.org/10.5518/700 (Holden, Palmer, & Brown, 2019). The rest of the data used are available via the Dryad Digital Repository https://doi.org/10.5061/dryad.tq4qr23 (Ashby & Heinemeyer 2019).

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REFERENCES

Amos, I. (2014). Cut heather burning for sake of the environment. *The Scotsman*. Retrieved from https://www.scotsman.com/news/environment/cut-heather-burning-for-sake-of-the-environment-1-3558555

Armstrong, A., Holden, J., Luxton, K., & Quinton, J. (2012). Multi-scale relationship between peatland vegetation type and dissolved organic carbon concentration. *Ecological Engineering*, *47*, 182–188. https://doi.org/10.1016/j.ecoleng.2012.06.027

Armstrong, A., Waldron, S., Ostle, N. J., Richardson, H., & Whitaker, J. (2015). Biotic and abiotic factors interact to regulate northern peatland carbon cycling. *Ecosystems*, *18*, 1395–1409. https://doi.org/10.1007/s10021-015-9907-4

Ashby, M. A., & Heinemeyer, A. (2019). Data from: Prescribed burning impacts on ecosystem services in the British uplands: A methodological critique of the EMBER project. *Dryad Digital Repository*, https://doi.org/10.5061/dryad.tq4qr23

Avery, M. (2014). An ecosystem disservice. markavery.info. Retrieved from https://markavery.info/2014/10/01/ecosystem-disservice/

Bawden, T. (2014). Grouse shooting 'is warming planet' as peatlands burned to improve conditions for birds. *The Independent*. Retrieved from https://www.independent.co.uk/environment/climate-change/grouse-shooting-is-warming-planet-as-peatlands-burned-to-improve-conditions-for-birds-9765659.html

Bell, M. C., Ritson, J. P., Verhoef, A., Brazier, R. E., Templeton, M. R., Graham, N. J., … Clark, J. M. (2018). Sensitivity of peatland litter decomposition to changes in temperature and rainfall. *Geoderma*, *331*, 29–37. https://doi.org/10.1016/j.geoderma.2018.06.002

Brown, L. E., Holden, J., & Palmer, S. M. (2014). *Effects of moorland burning on the ecohydrology of river basins. Key Findings from the EMBER project*. Leeds, UK: University of Leeds.

Brown, L. E., Johnston, K., Palmer, S. M., Aspray, K. L., & Holden, J. (2013). River ecosystem response to prescribed vegetation burning on blanket peatland. *PLoS ONE*, *8*, e81023. https://doi.org/10.1371/journal.pone.0081023

Brown, L. E., Palmer, S. M., Johnston, K., & Holden, J. (2015). Vegetation management with fire modifies peatland soil thermal regime. *Journal of Environmental Management*, *154*, 166–176. https://doi.org/10.1016/j.jenvman.2015.02.037

Davies, G. M., Kettridge, N., Stoof, C. R., Gray, A., Ascoli, D., Fernandes, P. M., … Vandvik, V. (2016). The role of fire in UK peatland and moorland management: The need for informed, unbiased debate. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *371*, 20150342. https://doi.org/10.1098/rstb.2015.0342

Durance, I., & Ormerod, S. J. (2007). Climate change effects on upland stream macroinvertebrates over a 25-year period. *Global Change Biology*, *13*, 942–957. https://doi.org/10.1111/j.1365-2486.2007.01340.x

França, F., Louzada, J., Korasaki, V., Griffiths, H., Silveira, J. M., & Barlow, J. (2016). Do space-for-time assessments underestimate the impacts of logging on tropical biodiversity? An Amazonian case study using dung beetles. *Journal of Applied Ecology*, *53*, 1098–1105. https://doi.org/10.1111/1365-2664.12657

Gail, M. H., Wieand, S., & Piantadosi, S. (1984). Biased estimates of treatment effect in randomized experiments with nonlinear regressions and omitted covariates. *Biometrika*, *71*, 431–444. https://doi.org/10.1093/biomet/71.3.431

Glaves, D., Morecroft, M., Fitzgibbon, C., Owen, M., Phillips, S. K., & Leppitt, P. (2013). *The effects of managed burning on upland peatland biodiversity, carbon and water*. Natural England evidence review NEER004, Peterborough, UK.

Harper, A. R., Doerr, S. H., Santin, C., Froyd, C. A., & Sinnadurai, P. (2018). Prescribed fire and its impacts on ecosystem services in the UK. *Science of the Total Environment*, *624*, 691–703. https://doi.org/10.1016/j.scitotenv.2017.12.161

Hedley, S. (2013). *Vegetation survey of the EMBER study plots. Report to Natural England*. Chepstow, UK: Wild Plants and Vegetation.

Heinemeyer, A., Croft, S., Garnett, M. H., Gloor, E., Holden, J., Lomas, M. R., & Ineson, P. (2010). The MILLENNIA peat cohort model: Predicting past, present and future soil carbon budgets and fluxes under changing climates in peatlands. *Climate Research*, *45*, 207–226. https://doi.org/10.3354/cr00928

Holden, J., Palmer, S. M., Johnston, K., Wearing, C., Irvine, B., & Brown, L. E. (2015). Impact of prescribed burning on blanket peat hydrology. *Water Resources Research*, *51*, 6472–6484. https://doi.org/10.1002/2014WR016782

Holden, J., Palmer, S.M., & Brown, L.E. (2019) *EMBER plot locations*. University of Leeds. https://doi.org/10.5518/700

Holden, J., Wearing, C., Palmer, S., Jackson, B., Johnston, K., & Brown, L. E. (2014). Fire decreases near-surface hydraulic conductivity and macropore flow in blanket peat. *Hydrological Processes*, *28*, 2868–2876. https://doi.org/10.1002/hyp.9875

Johnson, E. A., & Miyanishi, K. (2008). Testing the assumptions of chronosequences in succession. *Ecology Letters*, *11*, 419–431. https://doi.org/10.1111/j.1461-0248.2008.01173.x

Noble, A., Palmer, S. M., Glaves, D. J., Crowle, A., Brown, L. E., & Holden, J. (2018). Prescribed burning, atmospheric pollution and grazing effects on peatland vegetation composition. *Journal of Applied Ecology*, *55*, 559–569. https://doi.org/10.1111/1365-2664.12994

Parry, L., Chapman, P., Palmer, S., Wallage, Z., Wynne, H., & Holden, J. (2015). The influence of slope and peatland vegetation type on riverine dissolved organic carbon and water colour at different scales. *Science of the Total Environment*, *527*, 530–539. https://doi.org/10.1016/j.scitotenv.2015.03.036

Pickett, S. T. A. (1989). Space-for-time substitution as an alternative to long-term studies. In G. E. Likens (Ed.), *Long-term studies in ecology* (pp. 110–135). New York, NY: Springer.

Pourhoseingholi, M. A., Baghestani, A. R., & Vahedi, M. (2012). How to control confounding effects by statistical analysis. *Gastroenterology and Hepatology from Bed to Bench*, *5*, 79.

Ritson, J., Graham, N., Templeton, M., Clark, J., Gough, R., & Freeman, C. (2014). The impact of climate change on the treatability of dissolved organic matter (DOM) in upland water supplies: A UK perspective. *Science of the Total Environment*, *473*, 714–730. https://doi.org/10.1016/j.scitotenv.2013.12.095

Schwarz, C. J. (2014a). *Analysis of BACI experiments* (pp. 705–804). Course Notes for Beginning and Intermediate Statistics.

Schwarz, C. J. (2014b). *An overview of environmental field studies* (pp. 1367–1415). Course Notes for Beginning and Intermediate Statistics. Retrieved from http://people.stat.sfu.ca/~cschwarz/CourseNotes/

Simmons, I. G. (2003). *The moorlands of England and Wales: An environmental history 8000 BC to AD 2000*. Edinburgh: Edinburgh University Press.

Webster, B. (2014). Burning of grouse moors linked to global warming. *The Times*. Retrieved from. https://www.thetimes.co.uk/article/burning-of-grouse-moors-linked-to-global-warming-0zlvb9jzzzm

Yallop, A. R., Clutterbuck, B., & Thacker, J. (2010). Increases in humic dissolved organic carbon export from upland peat catchments: The role of temperature, declining sulphur deposition and changes in land management. *Climate Research*, *45*, 43–56. https://doi.org/10.3354/cr00884

Zuur, A., Ieno, E. N., & Smith, G. M. (2007). *Analyzing ecological data*. Berlin, Germany: Springer Science & Business Media.

Zuur, A., Ieno, E., Walker, N., Saveliev, A., & Smith, G. (2009). *Mixed effects models and extensions in ecology with R*. New York, NY: Springer.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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