Report 1:

The effects of managed burning on upland peatland biodiversity, carbon and water.

A review of the post-Glaves et al. (2013) evidence

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Peer review by Dr Gavin B. Stewart, Newcastle University (Appendix A)

Executive Summary: Key differences between conclusions drawn from evidence up to 2013 review compared to 2013-2020

Summary

Fundamental changes to the evidence base now disagrees with previous science

These changes should inform policy and any proposed regulation change, the England Peatland Strategy and Natural England's position on restoration burning

- Burned areas of blanket bog **ARE** capable of carbon capture.
- Production of charcoal during managed burning has a **POSITIVE** impact on long-term carbon storage.
- Burning **DOES NOT** cause water discolouration
- Controlled burning reduces fuel loads and helps **PREVENT AND LIMIT WILDFIRES**
- Over abundance of heather is **LIMITED** by burning. Environmentally important Sphagnum **MOSS RECOVERS** from 'cool' managed burning within three years.

Introduction

Natural England reviewed the science evidence base on heather burning up to 2013 and found it damaging for water colour, carbon storage and biodiversity. Following a dispute resolution process, NE and MA undertook to review the science from 2013- present following an agreed and consistent method. Peer Review was conducted by an independent scientist of NE's choosing.

Findings

1. Water Quality and storage

Water colouration: Glaves concluded that here was strong evidence that burning increased colour and so too does a heather dominant sward. However, updated evidence concludes that there is neutral effect – burning does not cause an increase or decrease in colouration. This disagrees with Glaves.

Glaves found moderate evidence that burning was associated with an increase in pH and weak evidence that the water table depth becomes shallower post burn. Fresh evidence is inconsistent with both neutral and slightly negative effects found for pH and also inconsistent on water table depth effect with higher and lower WTD found on burnt areas compared to unburnt or not recently burnt controls.

2. Carbon

Glaves concluded that comparing 10-year rotation plots and plots unburnt since 1954, burning reduced peat accumulation and reduced above and below ground carbon storage compared to no burning and carbon loses through burning in conversion to char. The updated evidence base disagrees with these three assertions. New evidence on whether peat is accumulated in burnt areas is now neutral not negative and concludes that burnt areas of blanket bog accumulate rather than lose carbon in the peat profile. The rate of accumulation in flat and wet areas of blanket bog subject to longer burning rotations of circa 20 years appears broadly the same as that recorded in unburnt or not recently burnt areas. Additionally, there is now consistent but very weak evidence that the production of charcoal during managed burning has positive impacts on long-term carbon storage - which therefore requires more study.

Glaves concluded that here was strong evidence that burning increased dissolved organic carbon (DOC)but updated evidence is consistent in that there is neutral effect – burning does not cause an increase or decrease in DOC disagreeing with Glaves.

Glaves concluded that burning resulted in an increase in small scale bare ground but the updated evidence reveals this is a transient effect lasting four to ten years.

3. Biodiversity

Flora – The concern of Glaves was that burning caused heather dominance which may affect the structure and function of Blanket bog. Whether burning was the original cause or not, (it is difficult to unpick other factors such as drainage) the evidence base now concludes that *Calluna vulgaris* becomes more abundant and eventually dominant with increasing time since burn, even in wetter areas and is highest on unmanaged areas whilst abundance is lowest on recently and/or frequently burnt areas. (See consequences of increasing abundance for water colouration and fuel load for wildfire severity).

Both reviews reveal inconsistent evidence on the effects on vegetation diversity, surface topography and Sphagnum moss diversity but the new review concludes that burning has a neutral effect on Sphagnum abundance and after initial damage done by low severity fire, the *Sphagnum capillifolium* almost fully recovers within three years and in high severity fires shows signs of recovery in that time period. Lower 'cool burn' severities cause minimal damage to *S.capillifolium* plants relative to unburnt controls.

Moderate evidence in Glaves concluded that the diversity and composition of aquatic Invertebrates assemblages changed including declines in mayfly and stonefly. The latest evidence is inconsistent in the abundance of pollution intolerant aquatic invertebrates so disagrees with Glaves.

4. Wildfire

Glaves found moderate evidence that fuel load and structure are critical factors in fire behaviour particularly in 'fireline' intensity (heat output per unit length of fire front) and rate of spread, although residence time and depth of penetration of lethal temperatures in to soil are important in determining severity of impact. Yet little evidence on the types of burning practice taking place in the English uplands including the 'extent' to which 'cool burning' is practiced was found. Burning reduces fuel load and may therefore have benefits for fire risk management and recognised the increased need for fire risk management as climate change scenarios become a reality. There was moderate evidence that 'heather moorland' in the Peak District, which was mostly managed by rotational burning, is less prone to the occurrence of wildfires than other moorland habitats.

Even the latest data on burning extent and frequency is ten years out of date and may have now changed with extensive wildfires, some very severe, having occurred in the last three years.

NE position on restoration burning - February 2018

It was always proposed as guidance to how they would consent application for restoration burning and would be updated in the light of new science.

"…..burning on blanket bog is generally considered to be harmful." (our emphasis).

Is the current evidence base supportive of this 'generally considered' position? For carbon storage, water quality and biodiversity the harmful effects concluded by Glaves, do not now appear to be upheld by the up to date evidence base.

"The UK government is responding to infraction proceedings from the EU requiring measures to halt deterioration of blanket bog condition as a result of regular burning." (our emphasis).

Are we still sure that the evidence base consistently and strongly links regular burning with the deterioration of blanket bog given the findings of this review?

"We remain committed to long term restoration plans which focus on a range of outcomes to be achieved from functioning blanket bog." (our emphasis).

If carbon storage, clean water and peat accumulation are key outcomes from functioning blanket bog, the evidence suggests that these outcomes can be delivered on flat and wet blanket bog areas, with a burn cycle of 20 years.

Conclusion

The time is now right to review Natural England's February 2018 position statement which guides its decisions on consenting burning and examine the circumstances in which burning may be a necessary tool to accelerate peatland restoration where restoration is impeded through over dominant heather but also where the structure and function of the site is intact but will deteriorate if burning is removed. Adaptive management through test and trials across multiple sites is the recommended approach to explore the best balance of outcomes under differing conditions.

Due to Climate Change the increased threat and impact from severe wildfires must now also be taken into account in terms of mitigating damage to structure and function of blanket bog.

A REVIEW OF THE POST-GLAVES ET AL. (2013) EVIDENCE:

INVESTIGATING THE EFFECTS OF MANAGED BURNING ON UPLAND PEATLAND BIODIVERSITY, CARBON, GREENHOUSE GAS EMISSIONS AND WATER.

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Burning on peatlands evidence statement by Dr Gavin B. Stewart and Dr Mark A. Ashby

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Burning on peatlands evidence statement by Dr Gavin Stewart, independent peer review

Purpose of the review

To summarise the updated evidence-base regarding peatland burning and ascertain key implications for policy, practice and research.

Summary of updated evidence

The evidence-base underpinning decisions about burning management is highly uncertain despite the plethora of papers published on the topic. The three major causes of uncertainty are i) difficulties synthesising studies measuring different outcomes on different spatial and temporal scales ii) high inconsistency in effects across multiple studies iii) high risk of bias resulting from deficiencies attributing causation and/or high potential for confounding. Interpretation of recent evidence, reviewed by Ashby differs from the interpretation of older evidence reviewed by Glaves, notably with respect to *Sphagnum* abundance and carbon accumulation. The impact of burning on the former is heavily context-dependent and varies in relation to post-burning succession. The latter is subject to a fierce academic debate that remains polarised and unresolved. Uncertainties in the evidence base are exacerbated by changing climatic baselines which may interact with floristic responses, carbon budgets, wildfire frequency and other important components of peatland systems. Further uncertainty is added by habitat heterogeneity, particularly for large scale studies which may incorporate both deep and shallow peats.

Implications for policy and practice

Deficiencies in the evidence-base necessitate decision-making under high uncertainty. One approach is to utilise the precautionary principle to minimise potential deleterious effects. This may be particularly appropriate for high-value sites on deeper peats, particularly where hydrological functioning is intact or easily restored. An alternative approach is to utilise an adaptive management framework whereby different management is undertaken at different sites subject to monitoring outcomes. Such an approach mitigates uncertainty by hedging and avoiding a one size fits all solution. It can also facilitate evidence acquisition, especially if this is built into the policy. This may be a viable option on peatlands with a lower conservation value where ecosystem service provision and sporting interest may be easier to align.

Implications for Research

The current deficiencies in the evidence-base are unlikely to be resolved by the accumulation of more studies alone. A more coherent framework is required based around a consensus regarding the core common outcomes required for studies of peatland management. This requires augmenting with work ascertaining how research-intensive measurements relate to easily measurable surrogates that could be collated at scale by automated sensors, remote sensing, citizen scientists and land managers. Large scale long term studies are required, which may be more cost-effective if surrogate outcomes have been identified, and comparator treatments are implemented by existing land managers. Incorporating elements of randomisation or adaptive trial design would help resolve uncertainties regarding causation.

Further information

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Bias Statement

This evidence briefing was prepared jointly by Gavin Stewart and Mark Ashby following peer review (GS) and authorship (MA) of an updated review of evidence funded by the Moorland Association. Peer review was undertaken at the bequest of Natural England and the Moorland Association. Open science and evidence synthesis have important roles in reconciling stakeholders with polarised beliefs and values about peatland management and allowing the development of a robust evidence-base in this domain.

Summary and key findings

Background

In 2013, Glaves et al. (2013) published a systematic review on "*The effects of managed burning on upland peatland biodiversity, carbon and water (NEER004)*". Since then, a substantial amount of evidence has emerged. However, rather than clarifying our understanding, the emerging evidence seems to have intensified the scientific debate about the use of managed burning on peatland ecosystems in the UK. In an attempt to provide clarity for land managers and policymakers, the Moorland Association commissioned a review of the evidence that has emerged since Glaves et al. (2013).

Review question

The overarching review question is: What are the effects of managed burning on the maintenance and restoration of upland peatland biodiversity, carbon, soil and water?

Objectives

This review has four objectives:

1. To produce a coded Excel database of post-Glaves et al. (2013) studies that can be used and expanded upon by researchers and policymakers moving forward as the basis of an up-to-date 'living review'.

2. To critically appraise and summarise the post-Glaves et al. (2013) evidence.

3. To highlight contradictions and similarities between the findings summarised in this review and those reported by Glaves et al. (2013).

4. To determine research gaps and priorities.

Search strategy

Evidence searches we conducted in four stages. First, we used a standardised search term to search the title, abstract and keywords of articles contained within the Web of Science and Scopus online databases. Second, we examined the reference lists of six recent and relevant literature reviews. Third, we searched the title, abstract and subject keywords of PhD and

MSc theses contained within the Ethos British Library online database. Finally, we added any articles known to the authors that were not picked up during stages one to three.

Inclusion criteria

We used the following inclusion criteria to accept or reject studies for review:

1. The study must have been published since 2012 (inclusive).

2. The study must not have been included within Glaves et al. (2013).

3. The study must be an original empirical investigation. Modelling studies, systematic/literature reviews, meta-analyses, commentaries, and descriptive books, book chapters and reports were not included within this review. However, if relevant, they were categorised (by reference type) and put within a table in the appendices.

4. The study must focus on temperate and boreal peatland in the northern hemisphere (especially blanket bog but including other bogs/mire/fen/wet heath), biodiversity (flora and fauna), carbon sequestration, GHG emissions, water (quality and flow), soil (erosion, moisture, temperature and chemistry), and (managed) burning. In general, references that did not specifically relate to burning were excluded. However, to address the potential indirect effects of burning on vegetation composition and structure in relation to sub-questions (b) (fauna), (c) (carbon sequestration and GHG emissions) and (d) (water), references relating to the effects of changes in vegetation composition and structure were accepted.

5. Studies must not solely focus on dry heath, mineral soils, forest/woodland/trees, tropical/arctic/tundra and wildfire (unless related to the effect of managed burning).

Data collection and analysis

Articles accepted for inclusion within this review were separated into individual studies and summarised using a range of coding variables and critical appraisal questions. Critical appraisal data was used to assign each study a quality rating based on their ability to ascribe causation. The quality ratings used were very high quality" (+++), "high quality" (++), "medium quality" (+) and "low quality" (-). Evidence for a range of outcome measures was summarised using a narrative synthesis approach. We also noted whether the evidence for a given outcome agreed with or contradicted the corresponding evidence outlined in Glaves et al. (2013).

Main findings

Sixty-two studies derived from 65 different articles were included in this review. These studies provided evidence for 55 different outcome measures. Most studies adopted a correlative, short-term and plot-scale approach to assessing burning impacts. Consequently, the overall quality of evidence for each outcome measure is low. Furthermore, the majority of outcome measures (64%) are supported by inconsistent evidence.

The strongest and most consistent evidence is for *Sphagnum* (principally *S. capillifolium*) abundance. Specifically, the evidence included in this review suggests that managed burning has a neutral impact on *Sphagnum* abundance within upland peatlands. Finally, the evidence for 23 of the outcome measures assessed is inconsistent with the findings presented in Glaves et al. (2013). Notable contradictions include carbon accumulation, dissolved organic carbon fluxes, water colour and *Sphagnum* abundance.

Conclusions

The contradictory nature and low quality of the evidence mean that it is difficult to draw firm conclusions about the impacts of burning on upland peatland ecosystems. As such, it would also be unwise to make any policy recommendations. However, we do have a series of general research recommendations that are informed by our findings:

1. Future studies must investigate burning impacts on upland peatlands using a robust and real-world approach. A robust approach would be the adoption of an experimental design that can accurately ascribe causality, such as a randomised controlled before-and-after trial. A real-world approach is an approach which examines burning in the same way upland land managers apply it, e.g., every year, multiple patches of varying size (but usually ~2500 m^2) are burnt on rotation across an extensive area of moorland using rotations that are suited to the local environmental (i.e. growing) conditions.

2. Both the pre- and post-Glaves et al., 2013 evidence must be collated and categorised.

3. We need to develop an objective approach for summarising the highly heterogeneous burning evidence base.

4. We also need to develop a series of standardised protocols for measuring peatland ecosystem services. This would enable researchers to assess the impact of different land management options using objective approaches, such as meta-analysis.

Contents

1. Introduction

In 2013, Glaves et al. (2013) published a systematic review on "*The effects of managed burning on upland peatland biodiversity, carbon and water (NEER004)*". Since then, a substantial amount of new evidence has emerged (e.g. Harper et al., 2018). Yet, rather than clarifying our understanding, the emerging evidence seems to have intensified the scientific debate surrounding the impacts of managed burning on peatland ecosystems in the UK (e.g. Brown et al., 2016; Davies et al., 2016b; Davies et al., 2016c; Douglas et al., 2016a; Ashby and Heinemeyer, 2019a; Ashby and Heinemeyer, 2019b; Baird et al., 2019; Brown and Holden, 2019; Evans et al., 2019; Heinemeyer et al., 2019b; Marrs et al., 2019b). Indeed, some peatland researchers argue that the evidence suggests the overall effect of burning on peatlands is unclear due to insufficient, contradictory or unreliable evidence (Davies et al., 2016b; Ashby and Heinemeyer, 2019a; Ashby and Heinemeyer, 2019b; Marrs et al., 2019b). Other peatland researchers challenge this assessment and assert the evidence shows that burning is significantly damaging to UK peatlands and the ecosystem services they provide (Brown et al., 2016; Douglas et al., 2016a; Baird et al., 2019; Brown and Holden, 2019).

Debate further intensified in 2016 when, in response to complaints submitted by the Royal Society for the Protection of Birds (RSPB, 2016), the European Commission threatened legal action (i.e. infraction proceedings) against the UK government if it failed to put a stop to rotational burning on blanket bog habitats within English Special Areas of Conservation (European Commission, 2017). The UK government responded by adopting a voluntary approach to stopping rotational burning on blanket bog habitats within SACs, with burning only being allowed as a one-off for restoration purposes under very strict criteria (Natural England, 2019a; Natural England, 2019d; Natural England, 2019c; Natural England, 2019b).

In an attempt to provide clarity, the author (Mark Ashby) was approached and contracted by the Moorland Association to collate and synthesise the evidence that has emerged since Glaves et al. (2013). However, even though there is some value in reviewing the post-Glaves et al. (2013) evidence, it would be much more valuable to researchers, land managers and policymakers if the entire evidence base were reviewed. Such a review would enable one to ascertain whether the cumulative evidence base changes any of the conclusions outlined in Glaves et al. (2013). Nevertheless, at this stage, Natural England[1] suggested it

[1] Natural England were consulted during every stage of the review process.

would be more appropriate to collate and synthesise the most recent and unreviewed evidence.

1.1. The review topic

1.1.1. What is considered in this topic review?

This review considers the effects of burning on upland peatland habitats, and the effects on carbon, soil, and water (quality and flow) related ecosystem services.

1.1.2. The overarching review question

The overarching review question is: What are the effects of managed burning on the maintenance and restoration of upland peatland biodiversity, carbon, soil and water?

The following sub-questions were the focus of the topic review (all but sub-question h are taken from Glaves et al., 2013):

a) **Flora -** What are the effects of managed burning on the maintenance and restoration of the characteristic floristic composition, structure and function of upland peatland habitats?

b) **Fauna -** What are the effects of managed burning on the maintenance and enhancement of the characteristic fauna of upland peatlands either directly or indirectly through changes in vegetation composition and structure?

c) **Carbon sequestration and greenhouse gas emissions -** What are the effects of managed burning of upland peatlands on carbon sequestration and greenhouse gas (GHG) emissions, either directly or indirectly through changes in vegetation composition and structure?

d) **Water quality and flow-** What are the effects of managed burning of upland peatlands on water quality (including colouration, the release of metals and other pollutants) and water flow (including downstream flood risk), either directly or indirectly through changes in vegetation composition and structure?

e) **Fire ecology -** How do differences in the severity, frequency, scale, location, and other characteristics of burns (including 'cool burns') affect upland peatland biodiversity, carbon, water and soil?

f) **Wildfire -** Is there a relationship between managed burning of upland peatlands and 'wildfire' (risk, hazard, occurrence, severity, extent and damage)?

g) **Burning extent -** What is the extent, frequency, practice and type of managed burning (including 'cool Burning') on upland peatlands (including in relation to designated sites and water catchments)?

h) **Soils -** What are the effects of managed burning of upland peatlands on peat soils (erosion, temperature and chemistry), either directly or indirectly through changes in vegetation composition and structure?

1.1.3. Review objectives

This review has four objectives:

1. To produce a coded Excel database of post-Glaves et al. (2013) studies that can be used (and expanded upon) by researchers and policymakers moving forward. It is hoped that the evidence used by Glaves et al. (2013) will be added to this database and that both evidence bases form the basis of an up-to-date 'living review' (sensu Elliott et al., 2017).

2. To critically appraise and summarise the post-Glaves et al. (2013) evidence relating to the overarching review question and sub-questions.

3. To highlight contradictions and similarities between the findings summarised in this review and those reported by Glaves et al. (2013).

4. To determine research gaps and priorities.

1.1.4. Study inclusion criteria

To be included in this review, studies had to pass the following inclusion/exclusion criteria:

6. The study must have been published since 2012 (inclusive).

7. The study must not have been included within Glaves et al. (2013).

8. The study must be an original empirical investigation. Modelling studies, systematic/literature reviews, meta-analyses, commentaries, and descriptive books, book chapters and reports were not included within this review. However, if relevant, they were categorised (by reference type) and put within a table in the appendices.

9. The study must focus on temperate and boreal peatland in the northern hemisphere (especially blanket bog but including other bogs/mire/fen/wet heath), biodiversity (flora and fauna), carbon sequestration, GHG emissions, water (quality and flow), soil (erosion, temperature and chemistry), and (managed) burning. In general, references that did not specifically relate to burning were excluded. However, to address the potential indirect effects of burning on vegetation composition and structure in relation to sub-questions (b) (fauna), (c) (carbon sequestration and GHG emissions) and (d) (water), references relating to the effects of changes in vegetation composition and structure were accepted.

10. Studies must not focus on dry heath, mineral soils, forest/woodland/trees, tropical/arctic/tundra and wildfire (unless related to the effect of managed burning).

2. Methods

This review attempted to use a similar methodology to Glaves et al. (2013) but, due to several reasons (e.g. logistics), this could not always be achieved. Significant departures from the Glaves et al. (2013) methodology are highlighted throughout the subsequent sections.

2.1. General principles

During the review process, all the available studies providing evidence for the review sub-questions were systematically identified (a-h, listed in section 1.1.2 above). This involved sifting through a list of articles returned during systematic literature searches to ensure that the only articles included were those that met the pre-defined inclusion criteria.

The following PICO framework was used to focus searches on:

- **Population:** upland peatland habitats in England.
- **Intervention:** managed burning.
- **Comparison:** no burning, at least in recent decades.
- **Outcome:** impact of burning on the maintenance and restoration of upland peatland biodiversity, carbon, soil and water.

2.2. Evidence searches

2.2.1. Search term development and optimisation

Glaves et al. (2013) conducted evidence searches using different combinations of relevant search words and wildcard operators. In contrast, we used a fixed search term that contained a string of relevant search words and wildcard operators. Our search term was developed by testing different combinations of specific words and wildcard operators relating to (i) managed burning; (ii) peatland restoration; (ii) peatland habitats; and, (iv) soil, water, GHG sequestration and biodiversity-related ecosystem services. The search term was refined by cross-referencing the search results of different word and wildcard operator combinations to the reference lists of the six recent literature reviews on managed burning impacts within the British uplands (Brown et al., 2015a; Heinemeyer and Vallack, 2015; Davies et al., 2016b;

Thompson et al., 2016; Sotherton et al., 2017; Harper et al., 2018). This resulted in the final search terms listed in Table 1, which are the same apart from minor formatting differences to account for the syntax requirements of the different online databases used. Database searches were conducted using the advanced search function to restrict results to the English language and the period between 2012 and 2019 (November). A start date of 2012 was selected because the final search phase of Glaves et al. (2013) took place during 2012 (D. Stone pers. comm., June 6, 2019). Field codes were used to limit searches to the title, abstract and keywords of the articles within each database (Table 1).

Table 1. The search term we used during the Web of Science and Scopus database searches. Note how the search words and Boolean operators are identical, but the formatting is different (*e.g.* the use of parentheses, quotation marks and asterisk differs). TS and TITLE-ABS-KEY are field codes used in the separate databases that restrict the search to the title, abstract and keywords of an article.

Web of Science: TS=((burn* OR “fire”) AND (peat* OR heath* OR moor* OR “blanket” OR “bog” OR “mire”) AND (“habitat management” OR “biodiversity” OR “grouse” OR restor* OR bird* OR plant* OR “vegetation” OR sphagnum* OR invertebrate* OR insect* OR amphibian* OR reptile* OR mammal* OR “water quality” OR “water colour” OR “flow” OR “saturated” OR “dissolved organic carbon” OR “DOC” OR hydrolog* OR infiltrat* OR “soil” OR carbon budget* OR “carbon cycling” OR carbon flux* OR “carbon sequestration” OR carbon stock* OR “carbon storage” OR “wildfire” OR ecosystem* OR environment*))
Scopus: TITLE-ABS-KEY((burn* OR {fire}) AND (peat* OR heath* OR moor* OR {blanket} OR {bog} OR {mire}) AND ({habitat management} OR {biodiversity} OR {grouse} OR restor* OR bird* OR plant* OR {vegetation} OR sphagnum* OR invertebrate* OR insect* OR amphibian* OR reptile* OR mammal* OR {water quality} OR {water colour} OR {flow} OR {saturated} OR {dissolved organic carbon} OR {DOC} OR hydrolog* OR infiltrat* OR {soil} OR carbon budget* OR {carbon cycling} OR carbon flux* OR {carbon sequestration} OR carbon stock* OR {carbon storage} OR {wildfire} OR ecosystem* OR environment*))

2.2.2. Search strategy

The first stage of our search strategy involved using the following online databases to extract relevant peer-reviewed journal articles:

1. Web of Science
2. Scopus

These databases were searched in the order shown using the appropriate search term. Search results were then downloaded from each database into an EndNote file. The second stage of the search strategy involved examining the reference lists of the six literature reviews used during search term development to extract additional articles not picked up during stage one:

1. Harper et al. (2018), “Prescribed fire and its impacts on ecosystem services in the UK”.

2. Sotherton et al. (2017), “An alternative view of moorland management for Red Grouse *Lagopus lagopus scotica*”.

3. Davies et al. (2016b), “The role of fire in UK peatland and moorland management: the need for informed, unbiased debate”.

4. Thompson et al. (2016), “Environmental impacts of high-output driven shooting of Red Grouse *Lagopus lagopus scotica*”.

5. Brown et al. (2015a), “Effects of fire on the hydrology, biogeochemistry, and ecology of peatland river systems”.

6. Heinemeyer and Vallack (2015), “Potential techniques to address heather dominance and help support 'active' *Sphagnum* supporting peatland vegetation on blanket peatlands and identify practical management options for experimental testing”.

These reviews were examined in reverse chronological order for any additional references not been picked up during the literature database search. Any additional references were added to the Endnote database.

The third stage of the search strategy involved extracting relevant PhD and MSc theses using the EThOS e-theses database provided by the British Library website (https://ethos.bl.uk/Home.do). The advanced search function was used to carry out three separate searches that focussed on the title, abstract and subject keywords of the theses within the EThOS database (Figure 1). During each search, the following search string was used: “prescribed fire OR prescribed burning OR rotational burning OR heather burning OR muirburn” (Figure 1). Again, any additional studies retrieved during the EThOS searches were added to the EndNote database.

Finally, a small number of relevant studies known to the author were retrospectively added to the EndNote database because the search strategy failed to capture them, or they were released after the literature searches had concluded.

2.2.3. Removal of duplicates

After all the literature searches were completed, duplicates were removed from the EndNote database using the eight-step de-duplication methodology outlined in Appendix C. This method was taken and modified from Bramer et al. (2016). Due to the importance of page numbers during the de-duplication process, the EndNote display settings were changed so that reference 'Pages' were visible within the library window (Bramer et al., 2016). Then, steps 1-8 were followed until all duplicates were removed (Appendix C). Each step involved searching for duplicates using different combinations of EndNote fields (e.g. title, author, pages), with the final step being a manual scan and removal of duplicate references (Appendix C).

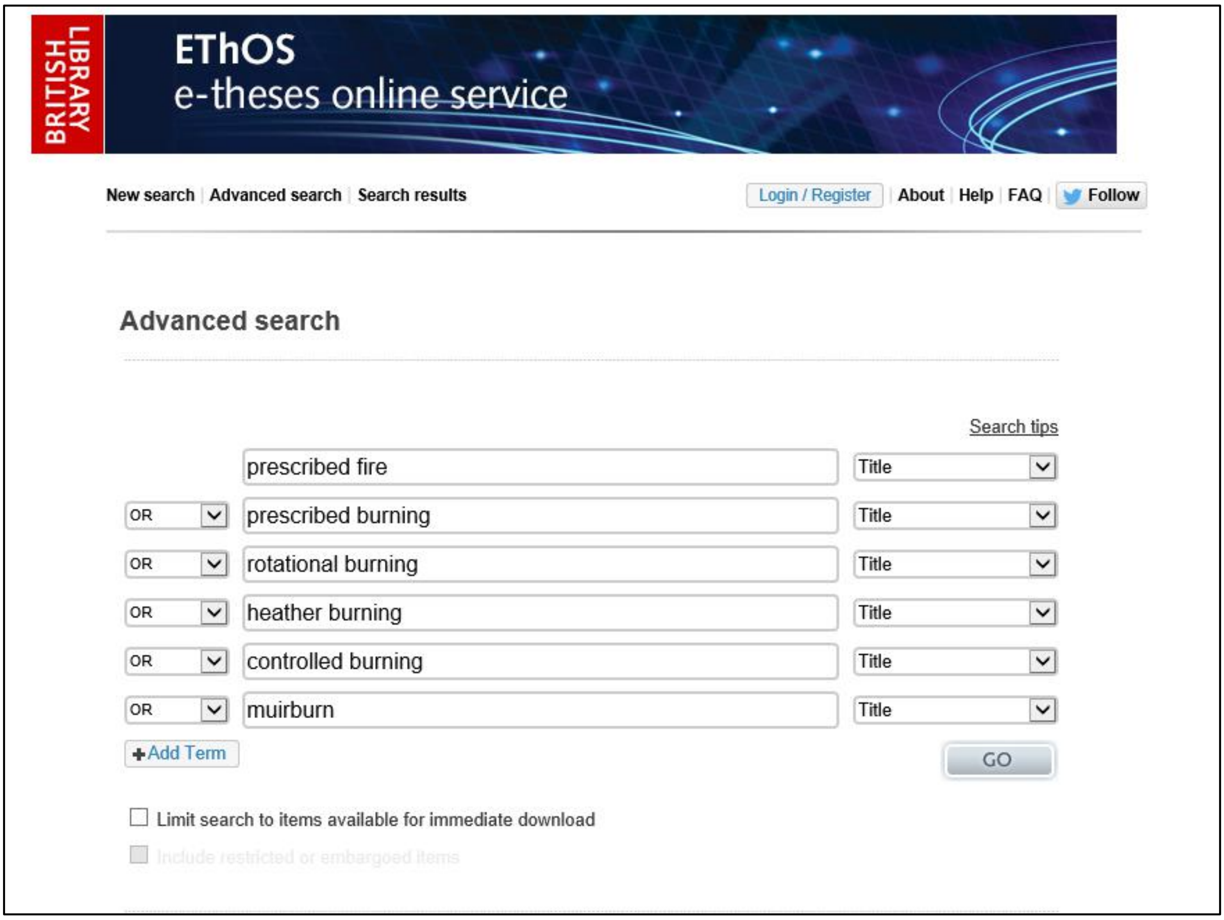


Figure 1. The search string entered into the EThOS e-theses database during the title, abstract and subject keyword advanced searches.

2.2.4. Study screening

Similar to Glaves et al. (2013), studies were screened for inclusion by a single reviewer (M. Ashby). However, unlike Glaves et al. (2013), quality assurance by a second reviewer was not carried out. Articles retrieved during evidence searches were screened for inclusion at two successive levels. First, all unduplicated references were exported from the EndNote database into a Microsoft Excel spreadsheet. Then, the date, title and abstract[2] of each article was examined to see whether it passed or failed each of the four review inclusion criteria (outlined in section 1.1.4. above). In cases of uncertainty (*e.g.* the title and/or abstract were implicitly but not explicitly relevant), the article was included. Second, articles accepted at stage one were read in full to ensure they met all the inclusion/exclusion criteria (see section 1.1.4.). Any articles accepted at this stage were grouped into studies and then entered into a Microsoft Excel spreadsheet using the following coding variables:

Column A: Study ID (unique numeric code given to each study)
Column B: First Author (surname and initial of the first author of the source article).
Column C: Title (Full title of the source article).
Column D: Year (the year in which the source article was published).
Column E: Harvard Reference (full Harvard reference of the source article).
Column F: Reference type (journal, report, book chapter, PhD theses, MSc theses).
Column G: Source (which search method was the source article obtained from).
Column H: Primary sub-question (the primary review sub-question that the study relates to).
Column I: Secondary sub-question(s) (the secondary sub-questions that the study relates to).
Column J: Country (the country or countries in which the study took place)
Column K: Region (the region or regions in which the study took place)
Column L: Study type (e.g. randomised control trial, non-randomised controlled trial, case-controlled trial, cohort study)
Column M: Study length (the amount of time [rounded up to full years] during which data collection started and finished for each study plot)
Column N: Linked study (if applicable, the name of the wider study or experiment which the article relates to, e.g. the Hard Hill experimental plots)
Column O: Surrogate predictor? (Were burning impacts measured directly? Yes/No)

[2] If an article did not have an abstract, then the reviewer read the summary, executive summary or introduction.

Column P: Habitat(s) (the habitat in which the study took place)
Column Q: Predictor variable(s) (the predictor variables used during the study)
Column R: Predictor variable notes (a brief description of the predictor variable)
Column S: Outcome variable(s) (the relevant outcome variables measured by the study)
Column T: Outcome variable measurement units (the units which were used to measure the relevant outcome variables)
Column U: Outcome variable notes (a brief description of the outcome variables)
Column V: Study findings (a brief description of the effect of the predictor variable on each of the outcome measurements investigated)
Column W: Study quality (the quality of the study – determined using the method outlined in section 2.3. below)
Column X: Study quality notes (explanatory notes about the quality designation given to each study)

The spreadsheet containing the data described above will be shared with scientists, land managers and policymakers working on fire impacts within the British uplands.

2.3. Critical appraisal of studies

Each study was critically appraised using 16 yes/no questions that, while considering several aspects of bias (e.g. internal and external validity), were primarily used to rank studies based on their ability to ascribe causality (Table 2). Using this approach, studies were ranked as "very high quality" (+++), "high quality" (++), "medium quality" (+) and "low quality" (-) based on the number of 'yes' responses returned for each of the critical appraisal questions (Table 3). Studies with a low risk of bias are those studies which combine a real-world approach with an experimental design robust enough to attribute causality (Table 3). A "real-world approach" is one which examines burning in the same way it is applied by upland land managers, e.g., every year, multiple patches of varying size (but usually ~2500 m^2) are burnt on rotation across an extensive area of moorland using rotations that are suited to the local environmental (i.e. growing) conditions.

This method of critical appraisal departs from that used in Glaves et al. (2013) in two ways. Firstly, our critical appraisal questions are different (See Appendix 12 in Stone, 2013). Secondly, instead of using a binary yes/no response, the critical appraisal questions used by Glaves et al. (2013) were answered using a graded response that related to whether the reviewer thought the study had low (++), moderate (+) or high (-) levels of bias (Stone, 2013). Each study was then classed as "high quality" (++), "medium quality" (+) and "low quality" (-) based on the general trend of responses across all the critical appraisal questions (i.e. overall, were there more ++, + or – responses) (*ibid*). This critical appraisal system was challenging to replicate when applying it to a small sample of studies included within Glaves et al. (2013). Therefore, a more explicit and repeatable critical appraisal methodology was developed. However, it is worth noting that both approaches are subjective and are, therefore, not definitive assessments of study quality (or bias).

Table 2. The 16 yes/no questions used to critically appraise each study included in this review.

1. Was there a spatial replicate? e.g. Were treatment measurements taken from multiple plots?
2. Was there a temporal replicate? e.g. Were treatment measurements taken across multiple time points?
3. Were significant confounding variables adequately controlled for during data analysis?
4. Was pseudoreplication avoided during data analysis? e.g. Multiple measurements were taken from individual monitoring units (e.g. plots) at a single point in time and/or across several points in time. Individual measurements were then used as replicates (instead of summing or averaging measurements taken from each survey plot) during data analysis without accounting for their lack of independence (e.g. by using appropriate nesting or random effects) (Davies and Gray, 2015).
5. Do the populations studied relate to the target habitats and setting(s) considered by this review (e.g. upland peatlands in the UK and particularly England)? This assessment considered whether the study was conducted in the UK and how representative it was of the English upland peatland resource. This required a comparison with the 'favourable condition' vegetation composition characteristics of upland peatlands in England (JNCC, 2009; JNCC, 2011).
6. Were treatments or study plots randomly allocated?
7. Was there a control? e.g. Was there an unburnt or not recently burnt control plot?
8. Was the study conducted in the field?
9. Was the study experimental?
10. Was the study conducted across multiple peatland sites? e.g. Data collection sites are considered separate if they are >5 km apart
11. Did the study measure burning impacts across more than one burning rotation? e.g. If managed burning was carried out on the burning treatment plots every ten years, then measurements were taken after at least two burns had been applied (once in the first ten years and once in the second ten years).
12. Did the study measure burning impacts across at least three different years within each burning rotation studied? e.g. After managed burning had been carried out, measurements were taken during at least three years before the plot was burnt again.
13. Were baseline measurements taken before burning treatments were applied?
14. Was the effect of burning studied at the catchment or moorland scale?
15. Did the treatments include different burn rotation lengths? e.g. 10-year and 20-year burn rotation treatments.
16. Did the treatments include different fire severities? e.g. low and high fire severity treatments (i.e. low and high fire temperature treatments which usually reflect low and high vegetation/soil moisture contents).

Table 3. The bias ratings ascribed to each study included in this review. Bias ratings were calculated using the critical appraisal questions in Table 2.

Quality rating	Criteria and definition
-	**Low-quality study.** A study that fails to pass questions 1-4.
+	**Medium quality study.** A study that passes questions 1-4 but fails questions 5-9.
++	**High-quality study.** A study that passes questions 1-9 but fails to pass questions 10-16.
+++	**Very high-quality study.** A study that passes questions 1-16.

2.4. Evidence synthesis

We followed the methodology set out in Glaves et al. (2013) and conducted a narrative synthesis of the evidence. We then produced evidence statements that described the quantity, quality, direction and consistency of the evidence for each outcome measure investigated by this review. Evidence consistency and direction were not assessed for outcome measures supported by a single study. Furthermore, evidence was only classed as consistent if ≥75% of the studies for a given outcome measure reported similar results (i.e. the direction of the effect was consistent across studies). Next, we made a series of general and outcome-specific research recommendations. Finally, in addition to providing evidence summary statements and research recommendations for each outcome measure, we also produced an evidence summary table. This table provides a condensed summary of the consistency, direction and strength of evidence for each outcome measure investigated by this review. It also notes whether any of our findings contradicted the findings described in Glaves et al. (2013). Evidence strength was assessed using the following criteria:

- **Strong evidence:** At least three very high-quality studies (+++) or eight high-quality studies (++) reporting consistent results.

- **Moderate evidence:** At least two very high-quality studies (+++) or five high-quality studies (++) reporting consistent results.

- **Weak evidence:** At least three high-quality studies (++) or eight medium-quality studies (+) reporting consistent results.

- **Very weak evidence:** Less than three high-quality studies (++) or less than eight medium-quality studies (+) reporting consistent results.

3. Characteristics of the post-Glaves et al. (2013) evidence base

3.1. Search results

Overall, 65 articles were included in this review, with 54 (83%) of these articles being obtained during the Web of Science search (Table 4). Of the 65 articles included in this review, 59 were from peer-reviewed journals, four were reports, and two were PhD theses. The 65 included articles were condensed into 62 individual studies for further analysis (Table 4).

Table 4. The number of articles retrieved during each search stage. Searches were carried out on the 25/11/2019.

Search method or review stage	Number of articles (number of articles accepted in this review)
1. Web of Science	1341 (54)
2. Scopus	316 (0*)
3. Harper et al. (2018)	25 (1)
4. Sotherton et al. (2017)	12 (3)
5. Davies et al. (2016)	25 (2)
6. Thompson et al. (2016)	12 (0)
7. Brown et al. (2015)	16 (2)
8. Heinemeyer & Vallack (2015)	2 (0)
9. EThOS British Library	5 (1)
10. Added Retrospectively	12 (2)
Total articles retrieved including duplicates	1765
Total articles retrieved minus duplicates	1505
Articles remaining after title, date, and abstract assessment	127
Articles remaining after the full-text assessment	65
Number of studies included within this review[1]	62

[1]The 65 articles included within this review were condensed into 62 studies.
* Most of the duplicates removed were studies retrieved during the Scopus search that had been picked up by We of Science.

3.2. Description of studies included within the review

Most of the studies included in this review were conducted in England (*n* = 43), followed by Scotland (*n* = 11), England and Scotland (*n* = 2), England, Scotland and Wales (*n* = 2), Norway (*n* = 2), Wales (*n* = 1), and Northern Ireland (*n* = 1) (Table 5). The majority of studies were correlational (*n* = 17) or case-control studies (*n* = 13) (Table 6). Sixty-five percent of studies (*n* = 40) were short-term (i.e. <10 years long), with the majority of short-term studies only collecting data over a single year (*n* = 20). However, ten paleoecological studies were included, and these studies examined data spanning for >1000 years.

Table 5. The number of accepted studies by country of origin.

Country	Number of studies
England	43
England & Scotland	2
England, Scotland & Wales	2
Scotland	11
Wales	1
Northern Ireland	1
Norway	2

Table 6. The number of accepted studies by type of study. In general, experimental studies (i.e. controlled trials) have the lowest risk of bias (Hurlbert, 1984; Smokorowski and Randall, 2017). The randomisation of treatments and collection of baseline data (i.e. a before-and-after study) further reduces bias (*ibid*).

Type of study	Number of studies
Randomised controlled before-and-after trial	6
Randomised controlled trial	9
Non-randomised controlled before-and-after trial	2
Non-randomised controlled trial	4
Before-and-after study*	1
Case-controlled study	13
Correlational study	17
Cohort study	3
Case report	8

Note: the total is 62 rather than 61 because one study used two approaches
*Differs from a randomised or non-randomised controlled before-and-after trial in that there is no control or treatment randomisation.

Forty of the 62 accepted studies measured burning impacts directly. Whereas, 22 of the accepted studies measured burning impacts indirectly by using vegetation structure (e.g. vegetation height), vegetation composition (e.g. cover of different peatland species), simulated ash deposition, simulated increased bulk density or charcoal macrofossils as proxies. Such variables can be used as proxies for burning management because:

- Upland peatland vegetation composition and structure are both influenced by managed burning (see Glaves et al., 2013 and references therein). For example, burning seems to initially promote the dominance of *Eriophorum*, followed by the long-term dominance of *Calluna vulgaris* (*ibid*). There is also a positive relationship between time since burn and vegetation canopy height within upland peatlands (Whitehead and Baines, 2018).

- Burning leads to the production of ash and charcoal (Allen, 1964; Worrall et al., 2013a; Leifeld et al., 2018) which can be added to the peat profile or removed via overland flow (Johnston and Robson, 2015; Heinemeyer et al., 2018).

- Managed burning can lead to an increase in peat bulk density (Noble et al., 2017; Heinemeyer et al., 2018).

3.3. Quality of studies included within the review

Only 18% of studies had a moderate risk of bias (*n* = 11), with the remaining 82% of studies having either a high (*n* = 26) or very high (*n* = 25) risk of bias (Table 7). More importantly, none of the studies included in this review were classified as having a low risk of bias. Consequently, no study can be said to have accurately or adequately assessed the impacts of burning on upland peatlands (i.e. by using a robust real-world approach).

Table 7. The number of accepted studies by the level of bias.

Study quality	Number of studies
Very high risk of bias	26
High risk of bias	25
Moderate risk of bias	11
Low risk of bias	0

Table 8 lists the number of "Yes" or "No" response to each of the critical appraisal questions used to assess study bias. Overall, most studies had a spatial or temporal replicate (*n* = 56 and *n* = 53, respectively), and avoided significant confounding effects (*n* = 47) or pseudoreplication (*n* = 53). Also, all but two studies related were not directly relatable to the English upland peatland resource. These two studies were conducted in the coastal wet heaths of Norway and were the only studies conducted on areas of shallow peat (<50cm) (Velle et al., 2014; Velle and Vandvik, 2014).

Table 8. The number of "Yes" or "No" responses to each of the critical appraisal questions used to assess study quality.

Critical appraisal question	Yes	No
1. Was there a spatial replicate? e.g. Were treatment measurements taken from multiple plots?	56	6
2. Was there a temporal replicate? e.g. Were treatment measurements taken across multiple time points?	53	9
3. Were significant confounding variables adequately controlled for during data analysis?	47	15
4. Was pseudoreplication avoided during data analysis?	53	9
5. Do the populations studied relate to the target habitats and setting(s) considered by this review?	60	2
6. Were treatments or study plots randomly allocated?	20	42
7. Was there a control? e.g. Was there an unburnt or not recently burnt control plot.	31	31
8. Was the study conducted in the field?	60	2
9. Was the study experimental?	24	38
10. Was the study conducted across multiple peatland sites?	28	34
11. Did the study measure burning impacts across more than one burning rotation?	2	60
12. Did the study measure burning impacts across at least three different years within each burning rotation studied?	6	56
13. Were baseline measurements taken before burning treatments were applied?	11	51
14. Was the effect of burning studied at the catchment or moorland scale?	20	42
15. Did the treatments include different burn rotation lengths?	14	48
16. Did the treatments include different fire severities?	6	56

Approximately half of the studies were conducted within a single site (*n* = 34) and did not have an experimental control (*n* = 32). Conversely, only a minority of studies included in this review:

- Were experimental (*n* = 24).
- Investigated the impact of different fire severities (*n* = 6) or burn rotation lengths (*n* = 14).
- Randomly assigned treatment or study plots (*n* = 20).

- Took measurements for more than three years within a rotation (n = 6) or across several burning rotations (n = 2).

- Took baseline measurements before treatments were applied (n = 11).

- Measured burning impacts at the catchment of moorland scale (n = 20)

4. Narrative review

4.1. Flora

Thirty-four studies investigated the effects of managed burning on upland peatland vegetation composition, structure and function (Fyfe and Woodbridge, 2012; Ward et al., 2012; Chambers et al., 2013; Lee et al., 2013b; Worrall et al., 2013a; Calladine et al., 2014; Velle et al., 2014; Velle and Vandvik, 2014; Alday et al., 2015; Blundell and Holden, 2015; Swindles et al., 2015; Taylor, 2015; McCarroll et al., 2016b; McCarroll et al., 2016a; Swindles et al., 2016; Chambers et al., 2017; Douglas et al., 2017; Grau-Andrés et al., 2017; McCarroll et al., 2017; Noble et al., 2017; Robertson et al., 2017; Fyfe et al., 2018; Ludwig et al., 2018; Milligan et al., 2018; Noble et al., 2018a; Noble et al., 2018b; Whitehead and Baines, 2018; Grau-Andrés et al., 2019a; Grau-Andrés et al., 2019b; Heinemeyer et al., 2019a; Heinemeyer et al., 2019c; Marrs et al., 2019a; Noble et al., 2019a; Noble et al., 2019b). Two of these studies were conducted outside the UK within the coastal wet heaths of Norway (Velle et al., 2014; Velle and Vandvik, 2014). Thirteen studies measured burning impacts indirectly by:

- Using paleoecological charcoal analysis (Fyfe and Woodbridge, 2012; Chambers et al., 2013; Blundell and Holden, 2015; Swindles et al., 2015; McCarroll et al., 2016b; McCarroll et al., 2016a; Swindles et al., 2016; Chambers et al., 2017; McCarroll et al., 2017; Fyfe et al., 2018), vegetation composition and structure (Calladine et al., 2014), artificial ash additions (Johnston and Robson, 2015; Noble et al., 2017), and changes to bulk density (Noble et al., 2017) as proxies for managed burning.

- Including managed burning as part of a ‘grouse moor’ management variable which also included predator control (Ludwig et al., 2018).

Paleoecology studies are considered separately within this sub-question evidence summary.

It is worth highlighting that seven of the 34 studies investigating the effects of managed burning on upland peatland vegetation used the Hard Hill experimental plots in Moor House National Nature Reserve, Upper Teesdale (Ward et al., 2012; Lee et al., 2013b; Alday et al., 2015; Milligan et al., 2018; Noble et al., 2018a; Marrs et al., 2019a; Noble et al., 2019b). The Hard Hill experiment was established in 1954/55, which makes it the longest-running study investigating the impacts of managed rotational burning and grazing in the UK (Marrs et al., 1986). Located within Moor House National Nature Reserve in Upper Teesdale

(British grid reference: NY 74124 33091), the experimental set-up consists of four 90 x 60 m experimental blocks (A, B, C and D), each of which are divided into six 30 x 30 m sub-plots (Noble et al., 2018a). The experimental blocks are positioned at regular intervals along a gentle hillslope, with block A being the lowest and block D being the highest (Marrs et al., 1986). At the start of the experiment each block was burnt in a single large burn: blocks A, B and D were burned in 1954 and block C was burned in 1955 (Lee et al., 2013a). Thereafter, two grazing treatments (fenced or grazed) and three burning treatments were applied (N = burnt in 1954 only; S = burnt in 1954 and every ten years after; L = burnt in 1954 and every 20 years after) (Rawes and Hobbs, 1979; Marrs et al., 1986). Treatments were assigned within each experimental block by using a randomised split-plot design as follows: four blocks (A-D) × two main treatments (fenced and grazed) × three sub-treatments (N, S, L) (Marrs et al., 1986). In addition to the main plots, unfenced reference plots (R) were established alongside each block outside of the initial 1954 burn areas (Fig 1) (Lee et al., 2013a). It is thought that these plots have not been burnt since 1923 (Rawes and Hobbs, 1979).

4.1.1. Vegetation diversity

Two low-quality studies (-) (Whitehead and Baines, 2018; Grau-Andrés et al., 2019a), two medium quality studies (+) (Velle et al., 2014; Velle and Vandvik, 2014) and three high-quality studies (++) (Milligan et al., 2018; Heinemeyer et al., 2019c; Marrs et al., 2019a) investigated the effect of managed burning on upland peatland vegetation diversity. Two of these studies used vegetation data from the Hard Hill experimental plots (Milligan et al., 2018; Marrs et al., 2019a). The Hard Hill data suggests that, since the start of the experiment (1954), vegetation diversity has marginally increased in the S plots (burnt every ten years) and L plots (burnt every 20 years), but decreased in the N plots (unburnt since 1954) (*ibid*).

A study by Grau-Andrés et al. (2019a) found that species and plant functional type diversity increased after a managed burn relative to unburnt controls. Conversely, Heinemeyer et al. (2019c) found no differences in vegetation diversity between burnt and unburnt peatland plots after four years post-burn. Furthermore, Whitehead and Baines (2018) measured vegetation species richness within unburnt control plots (last burnt >17 years before the start of the study), and plots burnt 1-2, 3-6, 7-10 and 11-17 years before the beginning of the study. Whitehead and Baines (2018) found that vegetation species richness differed across all treatments, but there was no clear pattern (*ibid*). However, when looking at just *Sphagnum* species richness, Whitehead and Baines (2018) found that: i) the unburnt control plots supported the lowest number of *Sphagnum* species; ii) plots burnt 1-2 years ago had the second-lowest numbers of *Sphagnum* species; and, iii) plots burnt 3-6, 7-10 and 11-17 years ago supported the highest number of *Sphagnum* species.

A further two studies examined the effect of managed burning on the vegetation communities within the coastal wet heaths of Norway (Velle et al., 2014; Velle and Vandvik, 2014). Both studies used before-and-after data from the same study plots and found that managed burning leads to an increase in vegetation diversity up to three years post-burn (*ibid*).

4.1.2. Vegetation structure

The impact of managed burning on upland peatland vegetation structure was assessed by three low-quality studies (-) (Robertson et al., 2017; Noble et al., 2018a; Whitehead and Baines, 2018), three medium quality studies (+) (Calladine et al., 2014; Douglas et al., 2017; Noble et al., 2019b) and four high-quality studies (++) (Alday et al., 2015; Heinemeyer et al., 2019a; Heinemeyer et al., 2019c; Noble et al., 2019a).

Four studies measured the impact of managed burning on the structure of the peatland surface (i.e. surface microtopography) (Noble et al., 2018a; Heinemeyer et al., 2019a; Noble et al., 2019a; Noble et al., 2019b). Heinemeyer et al. (2019a) found no differences in peatland surface microtopography between burnt and unburnt plots. Similarly, Noble et al. (2018a) collected data from the Hard Hill experimental plots and found that *Sphagnum* hummock height was similar within S plots (burnt every ten years) and R plots (unburnt since 1923). However, *Sphagnum* hummock height was greater within both S plots and R plots than in L plots (burnt every 20 years) and N plots (unburnt since 1954) (*ibid*). Conversely, Noble et al. (2019a) found that *Sphagnum capillifolium* height increased within unburnt control plots but decreased within burnt plots up to five months post-burn. Finally, Noble et al. (2019b) studied plots burnt one, five and ten years before the start of the study and found that moss depth (cm) generally increased with time since burn.

Seven studies also examined the impacts of managed burning on the structure of the vegetation canopy (usually *Calluna vulgaris* height) within upland peatlands (Calladine et al., 2014; Alday et al., 2015; Douglas et al., 2017; Robertson et al., 2017; Whitehead and Baines, 2018; Heinemeyer et al., 2019c; Noble et al., 2019b). Overall, all but one of these studies (Calladine et al., 2014), indicates that managed burning leads to changes in vegetation canopy height (Alday et al., 2015; Douglas et al., 2017; Robertson et al., 2017; Whitehead and Baines, 2018; Heinemeyer et al., 2019c; Noble et al., 2019b). Obviously, managed burning leads to an initial reduction in the height of the vegetation canopy. However, the height of the vegetation canopy subsequently increases with time since burn (Alday et al., 2015; Douglas et al., 2017; Whitehead and Baines, 2018; Heinemeyer et al., 2019c; Noble et al., 2019b). Interestingly, Robertson et al. (2017) found a positive relationship between variability in *C. vulgaris* canopy height and burning extent across their moorland study sites.

4.1.3. Sphagnum species

Five low-quality studies (-) (Noble et al., 2017; Noble et al., 2018a; Noble et al., 2018b; Whitehead and Baines, 2018; Grau-Andrés et al., 2019a), three medium quality studies (+) (Lee et al., 2013b; Grau-Andrés et al., 2017; Noble et al., 2019b) and five high-quality studies (++) (Taylor, 2015; Milligan et al., 2018; Heinemeyer et al., 2019c; Marrs et al., 2019a; Noble et al., 2019a) investigated the impacts of managed burning on *Sphagnum* species (herein known as "*Sphagnum*"). Five of these studies collected data from the Hard Hill experimental plots (Lee et al., 2013b; Milligan et al., 2018; Noble et al., 2018a; Marrs et al., 2019a; Noble et al., 2019a) and all but one study measured burning impacts on *Sphagnum* directly (Noble et al., 2017).

Most studies took two approaches to measure the effect of managed burning on *Sphagnum*. The first approach involved measuring the abundance of *Sphagnum*. Overall, these studies seem to suggest that burnt areas of upland peatland can support similar amounts of *Sphagnum* than unburnt or not recently burnt areas (Grau-Andrés et al., 2017; Milligan et al., 2018; Noble et al., 2018a; Whitehead and Baines, 2018; Grau-Andrés et al., 2019a; Heinemeyer et al., 2019c; Marrs et al., 2019a; Noble et al., 2019b). However, two studies reported that burning reduces the abundance of *Sphagnum* (Noble et al., 2017; Noble et al., 2018b), with one of these studies using increased peat bulk density and ash deposition as proxies for burning management (Noble et al., 2017).

The second approach involved measuring the heat damage inflicted by managed burning on *Sphagnum* plants (e.g. by measuring cell damage, photosynthetic capacity, net primary productivity, amount of bleaching or the amount of new growth) (Taylor, 2015; Grau-Andrés et al., 2017; Noble et al., 2019a). All of these studies show that managed burning leads to post-fire heat damage of *Sphagnum* plants (*ibid*). However, *Sphagnum* plants show signs of recovery within the space of three years (Taylor, 2015; Grau-Andrés et al., 2017). Thus, given the multiple studies suggesting that *Sphagnum* can be equally abundant on burnt and unburnt areas of upland peatland, the damage to *Sphagnum* plants caused by managed burning seems to be a transient effect. It is also worth considering that the damage inflicted by managed burning on *Sphagnum* plants is dependent on fire temperatures (Taylor, 2015; Grau-Andrés et al., 2017; Noble et al., 2019a), which is itself primarily driven by fuel load and vegetation moisture content (Davies et al., 2010b; Davies et al., 2016a; Grau-Andrés et al., 2018). For example, Noble et al. (2019a) found that, compared to an unburnt control, burning at low temperatures (≤137 ^{o}C) did not cause significant *S. capillifolium* cell damage.

An additional study by Lee et al. (2013b) used a third approach to investigate burning impacts on *Sphagnum*. This study measured the proportion of *Sphagnum* propagules in the top 7 cm of the peat profile within the Hard Hill plots. Lee et al. (2013b) found that the proportion of *Sphagnum* propagules within surface peat increased as burning rotation increased (i.e. *Sphagnum* propagules were lowest in the S plots and highest in the R plots) (*ibid*). This suggests that managed burning reduces the percentage of *Sphagnum* propagules within the peat layers, which contradicts the multiple studies suggesting that *Sphagnum* abundance is not adversely affected by managed burning (Grau-Andrés et al., 2017; Milligan et al., 2018; Noble et al., 2018a; Whitehead and Baines, 2018; Grau-Andrés et al., 2019a; Marrs et al., 2019a; Noble et al., 2019b).

It should be noted that the evidence on *Sphagnum* impacts included in this review is largely based on data for the most abundant peatland *Sphagnum* species: *S. capillifolium*. Indeed, because the abundance of other *Sphagnum* species is very low, many researchers decide to pool survey data for individual *Sphagnum* species during data analysis. However, the pooled data is often, but not always, dominated by *S. capillifolium*. Whereas, other researchers choose to focus on *S. capillifolium* because it is the most abundant *Sphagnum* species within their study site(s).

4.1.4. Eriophorum species

The impact of managed burning on *Eriophorum*[3] species (henceforth known as "*Eriophorum*") was examined by four low-quality studies (-) (Worrall et al., 2013a; Noble et al., 2018b; Whitehead and Baines, 2018; Grau-Andrés et al., 2019a), two medium quality studies (+) (Grau-Andrés et al., 2019b; Noble et al., 2019b) and five high-quality studies (++) (Ward et al., 2012; Taylor, 2015; Milligan et al., 2018; Heinemeyer et al., 2019c; Marrs et al., 2019a). Three of these studies used data collected from the Hard Hill experimental plots (Ward et al., 2012; Milligan et al., 2018; Marrs et al., 2019a). Across nine of the 11 studies, the abundance (percentage cover or biomass) of *Eriophorum* within burnt plots was greater or

[3] Some of the studies used graminoid abundance (cover or biomass). This was considered a proxy for *Eriophorum* abundance because *Eriophorum* species are usually the most dominant graminoid species in upland peatlands within the UK.

equal to that found in unburnt or not recently burnt plots (Ward et al., 2012; Worrall et al., 2013a; Milligan et al., 2018; Whitehead and Baines, 2018; Grau-Andrés et al., 2019a; Grau-Andrés et al., 2019b; Heinemeyer et al., 2019c; Marrs et al., 2019a; Noble et al., 2019b). Conversely, Noble et al. (2018b) found that *Eriophorum vaginatum* cover was greater within unburnt than burnt plots on upland peatland sites. Furthermore, three studies suggest that managed burning leads to an initial increase in the abundance of *Eriophorum* for up to ten years post-burn (Noble et al., 2018b; Whitehead and Baines, 2018; Noble et al., 2019b). However, after ten years have elapsed, *Eriophorum* abundance declines due to the rise in *C. vulagris* cover (*ibid*).

4.1.5. Calluna vulgaris

Four low-quality studies (-) (Worrall et al., 2013a; Noble et al., 2018b; Whitehead and Baines, 2018; Grau-Andrés et al., 2019a), five medium quality studies (+) (Lee et al., 2013b; Velle and Vandvik, 2014; Ludwig et al., 2018; Grau-Andrés et al., 2019b; Noble et al., 2019b) and six high-quality studies (++) (Ward et al., 2012; Alday et al., 2015; Taylor, 2015; Milligan et al., 2018; Heinemeyer et al., 2019c; Marrs et al., 2019a) investigated the effect of managed burning on *C. vulgaris.* Five of these studies collected data from the Hard Hill experimental plots (Ward et al., 2012; Lee et al., 2013b; Alday et al., 2015; Milligan et al., 2018; Marrs et al., 2019a).

Fourteen studies examined the impact of managed burning on *C. vulgaris* abundance (cover or biomass)[4]. Thirteen of these studies found that managed burning leads to a short-term reduction in *C. vulgaris* abundance (Ward et al., 2012; Worrall et al., 2013a; Velle and Vandvik, 2014; Alday et al., 2015; Taylor, 2015; Ludwig et al., 2018; Milligan et al., 2018; Whitehead and Baines, 2018; Grau-Andrés et al., 2019a; Grau-Andrés et al., 2019b; Heinemeyer et al., 2019c; Marrs et al., 2019a; Noble et al., 2019b). However, *C. vulgaris* then increases and starts to become dominant within areas that have remained unburnt for more than ten years (e.g. Milligan et al., 2018; Whitehead and Baines, 2018; Marrs et al., 2019a; Noble et al., 2019b). Thus, *C. vulgaris* abundance is lowest on areas of upland peatland that are recently and/or frequently burnt, and highest on unburnt or not recently burnt areas of upland peatland (Ward et al., 2012; Alday et al., 2015; Milligan et al., 2018; Whitehead and Baines, 2018; Heinemeyer et al., 2019c; Marrs et al., 2019a; Noble et al.,

[4] Some of the studies used dwarf shrub abundance (cover or biomass). This was considered a proxy for *C. vulgaris* abundance because *C. vulgaris* is usually the most dominant dwarfshrub species in upland peatlands within the UK.

2019b). Conversely, Noble et al. (2018b) found that burnt plots contained a greater abundance of *C. vulgaris* than unburnt plots (condition monitoring data).

A study by Lee et al. (2013b) used a different approach and investigated the effect of managed burning on *C. vulgaris* propagule banks within i) the litter and peat layers of a burning chronosequence in the peak district; and, ii) the peat layers of the Hard Hill experimental plots. The findings of this study show that i) across the burning chronosequence, *C. vulgaris* propagules were mainly found in the litter layer, which acted as a barrier of transfer to the peat layer; ii) *C vulgaris* propagules within the litter layer increased with time since burn; and, iii) across the Hard Hill experimental plots, *C. vulgaris* propagules within the peat layer increased with burning rotation length (i.e. *C. vulgaris* propagules were lowest in the S plots and highest in the N plots). In short, frequent burning reduces the amount of *C. vulgaris* propagules within the litter and peat layers in upland peatlands (*ibid*). In contrast, Heinemeyer et al. (2019c) found that burnt plots had higher levels of *C. vulgaris* germination than unburnt plots, but only for the first three years post-burn. In fact, Heinemeyer et al. (2019c) found that no *C. vulgaris* plants germinated from seed within unburnt plots throughout the four-year monitoring period.

4.1.6. Bare ground

The impact of managed burning on the creation of bare ground within upland peatlands was investigated by two low-quality studies (-) (Worrall et al., 2013a; Grau-Andrés et al., 2019a), three medium quality studies (+) (Velle and Vandvik, 2014; Grau-Andrés et al., 2019b; Noble et al., 2019b) and one high-quality study (Heinemeyer et al., 2019c). One study found that managed burning did not lead to an increase in the amount of bare ground (Worrall et al., 2013a). Conversely, five studies found that burning leads to an increase in bare ground, at least initially (Velle and Vandvik, 2014; Grau-Andrés et al., 2019a; Grau-Andrés et al., 2019b; Heinemeyer et al., 2019c; Noble et al., 2019b). However, bare ground percentage cover values recorded within quadrats located in burnt plots are usually <10% (Velle and Vandvik, 2014; Grau-Andrés et al., 2019a; Grau-Andrés et al., 2019b; Noble et al., 2019b). Moreover, Heinemeyer et al. (2019c) and Noble et al. (2019b) found that bare ground all but disappears four and ten years post-burn, respectively. Thus, managed burning leads to only a small-scale and transient increase in bare ground.

4.1.7. Paleoecology studies

Ten paleoecology studies were included in this review[5]. Two of these were medium quality studies (+) (Fyfe and Woodbridge, 2012; Fyfe et al., 2018), while the other eight were low-quality studies (-) (Chambers et al., 2013; Blundell and Holden, 2015; Swindles et al., 2015; McCarroll et al., 2016b; McCarroll et al., 2016a; Swindles et al., 2016; Chambers et al., 2017; McCarroll et al., 2017). Overall, nine of the ten paleoecology studies found that evidence of fire (wildfire or managed burning) within the peat profile (measured by calculating the number of charcoal macrofossils in the peat layers) was coincident with changes in upland peatland vegetation (measured by calculating the number of different plant macrofossils and pollen species in the peat layers) (Chambers et al., 2013; Blundell and Holden, 2015; Swindles et al., 2015; McCarroll et al., 2016b; McCarroll et al., 2016a; Swindles et al., 2016; Chambers et al., 2017; McCarroll et al., 2017; Fyfe et al., 2018). A consistent finding was a decrease in *Sphagnum* macrofossils being coincident with evidence of fire throughout the peat profile (Fyfe and Woodbridge, 2012; Chambers et al., 2013; Blundell and Holden, 2015; Swindles et al., 2015; McCarroll et al., 2016b; McCarroll et al., 2016a; Chambers et al., 2017; McCarroll et al., 2017).

4.2. Fauna

Nineteen of the 62 studies included in this review investigated the effect of managed burning on the fauna present within upland peatlands (Dallimer et al., 2012; Johnston, 2012; Turner and Swindles, 2012; Ward et al., 2012; Brown et al., 2013; Ward et al., 2013; Calladine et al., 2014; Douglas et al., 2014; Douglas and Pearce-Higgins, 2014; Johnston and Robson, 2015; Newey et al., 2016; Roos et al., 2016; Buchanan et al., 2017; Douglas et al., 2017; Ludwig et al., 2017; Robertson et al., 2017; Ludwig et al., 2018; Heinemeyer et al., 2019c; Littlewood et al., 2019). Eleven of these studies measured burning impacts directly (Johnston, 2012; Turner and Swindles, 2012; Ward et al., 2012; Brown et al., 2013; Douglas et al., 2014; Newey et al., 2016; Roos et al., 2016; Douglas et al., 2017; Robertson et al., 2017; Heinemeyer et al., 2019c; Littlewood et al., 2019), whereas seven studies measured burning impacts indirectly by using proxies such as different levels of ash deposition (Johnston and Robson, 2015), vegetation structure and composition (Ward et al., 2013; Calladine et al., 2014; Douglas and Pearce-Higgins, 2014; Roos et al., 2016; Buchanan et al., 2017), and general grouse moor management (which including managed burning alongside, vegetation cutting, predator control and reductions in grazing) (Ludwig et al., 2017; Ludwig et al., 2018).

[5] Studies that examine pollen, plant macrofossils and charcoal macrofossils down through the peat profile. This is done to investigate long-term vegetation change and, in some cases, drivers of vegetation change.

4.2.1. Birds

The impact of managed burning on upland peatland bird communities was examined by two low-quality studies (-) (Roos et al., 2016; Robertson et al., 2017) and ten medium quality studies (+) (Dallimer et al., 2012; Calladine et al., 2014; Douglas et al., 2014; Douglas and Pearce-Higgins, 2014; Newey et al., 2016; Buchanan et al., 2017; Douglas et al., 2017; Ludwig et al., 2017; Ludwig et al., 2018; Littlewood et al., 2019). Six of these studies measured burning impacts directly (Dallimer et al., 2012; Douglas et al., 2014; Newey et al., 2016; Douglas et al., 2017; Robertson et al., 2017; Littlewood et al., 2019). In contrast, six studies measured burning impacts indirectly by using proxies for burning management such as vegetation structure and composition (Calladine et al., 2014; Douglas and Pearce-Higgins, 2014; Roos et al., 2016; Buchanan et al., 2017), and general grouse moor management[6] (Ludwig et al., 2017; Ludwig et al., 2018). Furthermore, all twelve bird studies used a correlative study design.

The only consistent result that emerged from these studies is that, by promoting areas with shorter and/or more varied vegetation structure across a moorland, managed burning is likely to have a positive effect on *Pluvialis apricaria* populations within upland peatland habitats (Calladine et al., 2014; Douglas and Pearce-Higgins, 2014; Newey et al., 2016; Buchanan et al., 2017; Douglas et al., 2017; Littlewood et al., 2019). However, even if not recorded, managed burning is usually coincident with predator control in many upland areas, which makes it extremely hard to disentangle the relative effect of managed burning on upland bird species.

4.2.2. Aquatic invertebrates

Three low-quality studies (-) investigated the impact of managed burning on aquatic invertebrate communities within upland peatland streams (Johnston, 2012; Brown et al., 2013; Johnston and Robson, 2015). Two of these studies measured the impact of managed burning directly (Johnston, 2012; Brown et al., 2013). In contrast, Johnston and Robson (2015) used different levels of ash added to within stream mesocosm trays as proxies for managed burning (high, low and no ash additions).

Johnston (2012) and Brown et al. (2013) found that streams draining burnt catchments had slightly higher aquatic invertebrate biodiversity than streams draining

[6] General grouse moor management includes managed burning alongside vegetation cutting, predator control and reductions in grazing.

unburnt catchments. Furthermore, Johnston (2012) and Brown et al. (2013) also found that the abundance of pollution sensitive taxa (e.g. Ephemeroptera) was slightly lower in streams draining burnt catchments than in streams draining unburnt catchments (*ibid*). Conversely, both studies found that the abundance of pollution tolerant taxa (e.g. Chironomidae) was slightly higher in streams draining burnt catchments than in streams draining unburnt catchments (*ibid*). However, the studies of Johnston (2012) and Brown et al. (2013) confounded study site with treatment (managed burning versus no managed burning), and this was not controlled for during statistical analysis. Thus, we cannot be sure whether the results of these studies are due to burning management (managed burning versus no managed burning) or differences between sites. For example, the sites used by Brown et al. (2013) were geographically and environmentally distinct, with burnt catchments receiving less rainfall than unburnt catchments (Ashby and Heinemeyer, 2019a; Ashby and Heinemeyer, 2019b).

A third study by Johnston and Robson (2015) found that different levels of ash additions (high, low and no ash additions added to within stream mesocosm trays) had little effect of aquatic invertebrate communities.

4.2.3. Terrestrial invertebrates

A single high-quality study (++) examined the impact of managed burning on terrestrial invertebrates. This study, by Heinemeyer et al. (2019c), compared cranefly (Tipulidae) emergence between burnt and unburnt control plots (and mown plots) for three years post-management. Cranefly emergence was slightly higher within unburnt plots in the first year post-management (*ibid*). However, in year two and three, cranefly emergence was greater within burnt plots (*ibid*). Importantly, these findings were related to differences in soil surface moisture (top 8 cm) (*ibid*). For example, soil moistures of between 80-95% represent the optimal range for cranefly larval development and emergence (*ibid*). During the first post-management year (a dry year), Heinemeyer et al. (2019c) found that soil surface moisture within unburnt plots was within this optimum range, whereas soil surface moisture within burnt plots was below it (i.e. <80%). Conversely, in the second and third post-management years (both wet years), Heinemeyer et al. (2019c) found that soil surface moisture within burnt plots was within this optimum range, but soil surface moisture within unburnt plots was above it (i.e. >95%). In general, soil surface moisture was lower in burnt plots (*ibid*). Thus, while unburnt plots probably provide better conditions for cranefly emergence in dry and normal years, burnt plots provide better conditions for cranefly emergence in wetter years.

4.2.4. Soil microorganisms

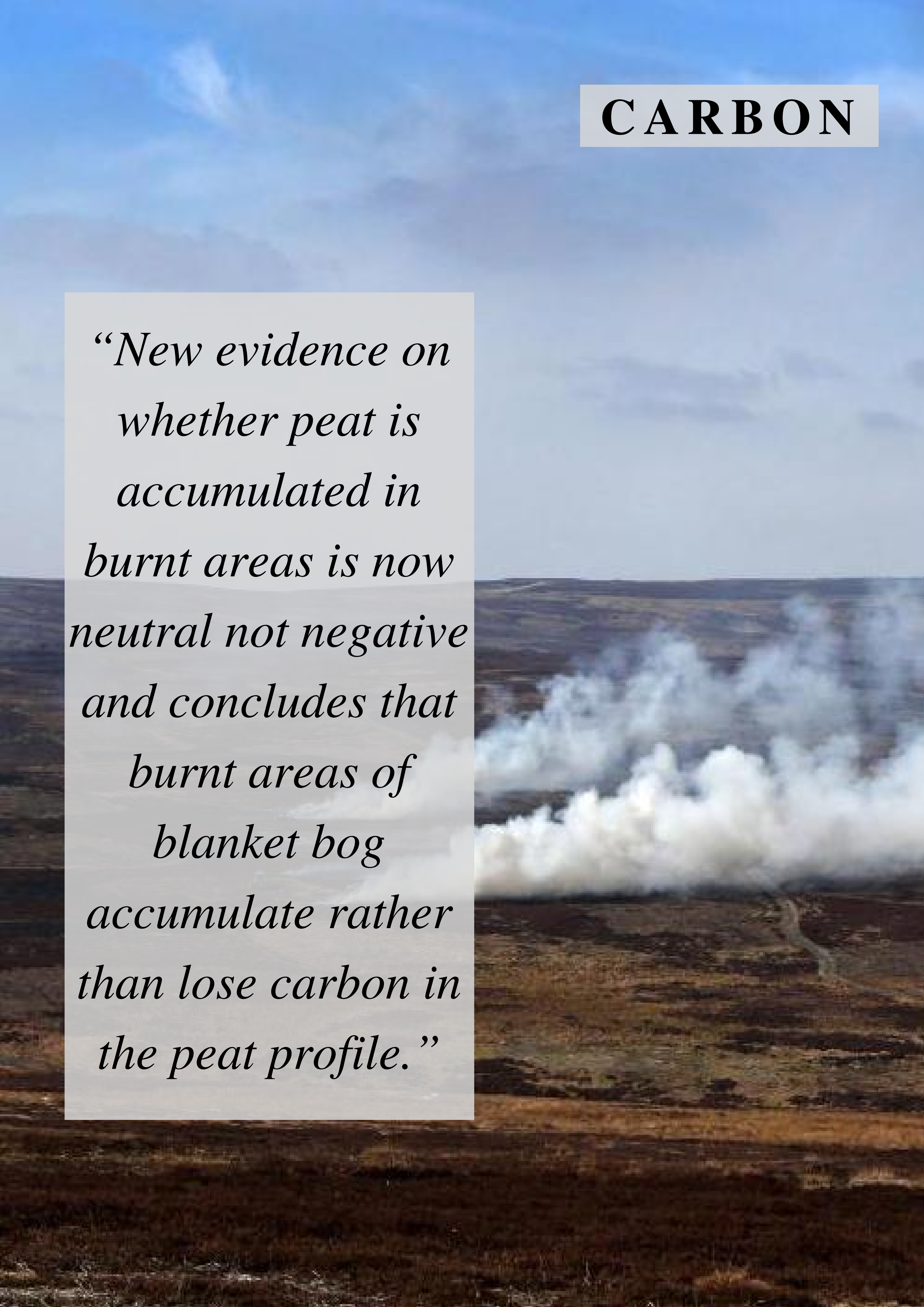
One low-quality study (-) (Turner and Swindles, 2012) and one high-quality study (++) (Ward et al., 2012) investigated the impact of managed burning on soil microorganisms. Ward et al. (2012) used two of the Hard Hill experimental burning treatments and found that S plots (burnt every ten years) had a lower soil fungal biomass than N plots (unburnt since 1954). Conversely, burning did not affect soil bacterial biomass (*ibid*). A second study by Turner and Swindles (2012) found differences in testate amoebae communities between burnt and unburnt areas of upland peatland. For example, while median Shannon diversity values were similar within unburnt and burnt areas of blanket bog, unburnt areas recorded the highest individual Shannon diversity value (*ibid*). Furthermore, the testate amoebae communities within burnt areas of blanket bog were slightly more indicative of drier conditions (i.e. lower water tables) (*ibid*).

4.3. Carbon sequestration and greenhouse gas emissions

A total of 13 studies investigated the effect of managed burning on carbon sequestration and/or GHG emissions (Ward et al., 2012; Ward et al., 2013; Worrall et al., 2013a; Worrall et al., 2013b; Clay et al., 2015; Dixon et al., 2015; Parry et al., 2015; Taylor, 2015; Walker et al., 2016; Heinemeyer et al., 2018; Grau-Andrés et al., 2019b; Heinemeyer et al., 2019c; Marrs et al., 2019a). Eight of these studies measured burning impacts directly (Ward et al., 2012; Worrall et al., 2013a; Worrall et al., 2013b; Clay et al., 2015; Taylor, 2015; Heinemeyer et al., 2018; Grau-Andrés et al., 2019b; Heinemeyer et al., 2019c; Marrs et al., 2019a), whereas four studies used vegetation composition (Ward et al., 2013; Parry et al., 2015; Walker et al., 2016) or structure (Dixon et al., 2015) as proxies for burning management.

4.3.1. Carbon and peat accumulation within upland peatland soil profiles

One medium quality study (+) (Heinemeyer et al., 2018) and one high-quality study (++) (Marrs et al., 2019a) investigated the effect of managed burning on peat and/or carbon accumulation within upland peatlands. Heinemeyer et al. (2018) used peat core analysis across three upland peatland sites subject to managed burning to investigate carbon accumulation within three time periods: 1700-1850, 1850-1950 and 1950-2015. Heinemeyer et al. (2018) found that there was considerable net carbon accumulation during all three time periods, which suggests that areas of blanket bog subject to managed burning accumulate,



CARBON

"New evidence on whether peat is accumulated in burnt areas is now neutral not negative and concludes that burnt areas of blanket bog accumulate rather than lose carbon in the peat profile."

rather than lose, carbon. Moreover, Heinemeyer et al. (2018) also found a positive relationship between carbon accumulation rates and charcoal macrofossil concentration throughout the peat profile (number of charcoal pieces per cm^3 of peat), which indicates that burning, via the production of charcoal, may have a positive effect on peatland carbon accumulation. The positive impact of low-severity fires on peatland carbon storage via charcoal production has also been highlighted by studies elsewhere (Leifeld et al., 2018; Flanagan et al., 2020).

A second peat core study by Marrs et al. (2019a) investigated the effect of managed burning on peat and carbon accumulation by using all three of the Hard Hill experimental plots (S, L and N plots) and the R plots outside the main experimental area. Marrs et al. (2019a) found that all the plots showed net carbon and peat accumulation. However, the frequently burnt S plots (burnt every ten years) accumulated significantly less peat and carbon than the R plots (unburnt since at least 1923). It is worth noting that the ten-year rotation of the S plots is not an appropriate burning rotation for many upland peatland sites, which, due to slow *C. vulgaris* growth rates (owing to cold and wet climates), are much more suited to the 20-year rotation of the L plots (Alday et al., 2015). Furthermore, Marrs et al. (2019a) also found no differences in peat height across plots, which means that the differences in peat accumulation between S and R plots are likely due to differences in peat density (i.e. peat density was greater in S plots) and organic carbon content (which was not directly measured) (*ibid*).

4.3.2. Upland peatland carbon fluxes

One low-quality study (-) (Clay et al., 2015), two medium quality studies (+) (Dixon et al., 2015; Grau-Andrés et al., 2019b) and five high-quality studies (++) (Ward et al., 2012; Ward et al., 2013; Taylor, 2015; Walker et al., 2016; Heinemeyer et al., 2019c) investigated the effect of managed burning (either directly or indirectly) on carbon dioxide fluxes. Three of these studies used indirect measurements to examine managed burning impacts on carbon fluxes. Firstly, an indirect study by Dixon et al. (2015) measured carbon fluxes across plots with increasing *C. vulgaris* canopy height. Dixon et al. (2015) found a negative relationship between canopy height and net ecosystem exchange (NEE) [7] and that there was no canopy height at which *C. vulgaris* dominated upland peatland would be a net annual sink of carbon

[7] Net ecosystem exchange is the sum of the carbon dioxide released when plants respire, and the carbon dioxide absorbed when plants photosynthesise. Thus, NEE can be positive or negative, with negative values indicating a carbon dioxide sink.

dioxide. Consequently, the authors suggest that turning upland peatlands into carbon sinks requires a shift away from *C. vulgaris* dominance (*ibid*).

Another indirect study by Walker et al. (2016) measured carbon fluxes across upland peatland plots subject to ambient or warmed climatic conditions and containing different combinations of plant functional types: dwarf shrubs, graminoids, bryophytes, mixed vegetation and bare peat. Walker et al. (2016) found that: i) ecosystem respiration flux (ER) was highest in plots in which dwarf shrubs (i.e. *C. vulgaris*) or graminoids (i.e. *Eriophorum*) were present; ii) artificial climate warming increased ER in the bare peat and dwarf shrub only plots, but had no effect on ER within the bryophyte, graminoid only or fully vegetated treatments (mixture of plant functional types); iii) under ambient conditions, the bryophyte only treatment led to an increase in the respiration of older carbon stocks (the mean age of carbon released was 412 years before present compared to only 40 years before present for the dwarf shrub only treatment); and, iv) under artificial climate warming conditions, the graminoid only treatment, dwarf shrub only treatment and mixed vegetation treatment all led to an increase in the respiration of older carbon stocks (the mean age of carbon released in each treatment was 300, 900 and 2100 before present, respectively).

The third and final indirect study was conducted by Ward et al. (2013), who used the same experimental plots as those used by Walker et al. (2016). Ward et al. (2013) measured NEE of carbon dioxide and found that plots containing dwarf shrubs (i.e. *C. vulgaris*) had the strongest carbon sink function, including dwarf shrub only plots, dwarf shrub and graminoid plots, and dwarf shrub and bryophyte plots.

The remaining five studies measured the impacts of burning on carbon fluxes directly. Clay et al. (2015) examined unburnt and burnt peatland plots that were burnt one, three, five, six, seven, eight, ten and 11 years before the start of the study. The findings suggested that the amount of carbon dioxide absorbed by plants during photosynthesis varied across all treatments, but plots burnt one and 11 years before the start of the study absorbed the highest and lowest amount of carbon dioxide, respectively (*ibid*). ER of carbon dioxide also varied across plots but was highest in the plots burnt one and ten years before the start of the study (*ibid*). Clay et al. (2015) also found that, in general, NEE was negative for young burns but positive for older burns and one out of the two unburnt control sites (i.e. younger burns are carbon sinks, and older burns are net emitters of carbon dioxide).

Taylor (2015) found that ER did not differ between burnt and unburnt plots spread across three upland peatland sites. Conversely, Grau-Andrés et al. (2019b) and Heinemeyer et al. (2019c) found that burnt plots emitted lower levels of carbon dioxide via ER than unburnt plots. However, both studies found that NEE was higher on burnt plots relative to unburnt controls (*ibid*). Heinemeyer et al. (2019c) collected baseline (pre-burn) data and found that burnt plots switch from a net carbon sink to a net carbon source after management, but carbon losses were decreasing over time. Finally, using two of the three Hard Hill treatments, Ward et al. (2012) found no differences in ER, gross primary productivity (GPP)[8] and NEE between the S plots (burnt every ten years) and N plots (unburnt since 1954).

4.3.3. Upland peatland methane fluxes

The effect of managed burning on upland peatland methane fluxes was investigated by one medium quality study (+) (Grau-Andrés et al., 2019b) and four high-quality studies (++) (Ward et al., 2012; Ward et al., 2013; Taylor, 2015; Heinemeyer et al., 2019c). Two of these studies found no differences in methane emissions between burnt and unburnt areas of upland peatland (Ward et al., 2012; Taylor, 2015). However, Grau-Andrés et al. (2019b) found that burnt plots had higher methane emissions than unburnt plots, especially in summer. Conversely, Heinemeyer et al. (2019c) found that burnt plots emitted less methane than unburnt plots in vegetated areas, but in unvegetated areas, burnt and unburnt plots emitted similar amounts of methane. Heinemeyer et al. (2019c) also found a weak positive correlation between the cover of *Eriophorum* species and methane fluxes across all study plots. Furthermore, an indirect study by Ward et al. (2013) found that upland peatland plots containing graminoids (*Eriophorum* species) and no dwarf shrubs (*C. vulgaris*) had the highest methane emissions under both ambient and warmed climatic conditions.

4.3.4. Upland peatland dissolved organic carbon fluxes

The impact of managed burning on upland peatland dissolved organic carbon (DOC) fluxes was investigated by one low-quality study (-) (Worrall et al., 2013b), two medium-quality studies (+) (Parry et al., 2015; Grau-Andrés et al., 2019b) and two high-quality studies (++) (Ward et al., 2013; Heinemeyer et al., 2019c). Three of these studies measured burning impacts directly (Worrall et al., 2013b; Grau-Andrés et al., 2019b; Heinemeyer et al., 2019c), whereas two studies investigated the effect of different plant functional types on upland peatland dissolved organic carbon fluxes (Ward et al., 2013; Parry et al., 2015). Firstly, Grau-Andrés et al. (2019b) and Heinemeyer et al. (2019c) found no differences in soil water DOC concentrations between burnt and unburnt peatland plots. Secondly, Worrall et al. (2013b)

[8] Gross primary productivity is the amount of carbon dioxide uptake by plants during photosynthesis.

investigated the impact of burning, cutting and no vegetation management (i.e. an unmanaged control) on soil water and overland flow DOC concentrations within an upland peatland. This study found that plots subject to burning or cutting treatments had lower soil water DOC concentrations, whereas overland flow DOC concentrations did not differ across treatments (*ibid*). Thirdly, Parry et al. (2015) tested how slope and vegetation composition (plant functional types) influence stream water DOC concentrations within 119 peatland catchments spanning three drainage basins. This study found that different plant functional types[9] had little influence on stream water DOC concentrations (*ibid*). Finally, Ward et al. (2013) found that the removal of dwarf shrubs (i.e. *C.vulgaris*) led to an increase in soil water DOC concentrations.

4.3.5. Charcoal production

The incomplete combustion of vegetation during wild or managed fires leads to the production of a carbon-rich substance called charcoal (Leifeld et al., 2018; Wei et al., 2018; Jones et al., 2019). Charcoal is resistant to oxidation[10], which means it has the potential to lock away large amounts of carbon when it is added to the soil profile on upland peatlands (Worrall et al., 2013a; Heinemeyer et al., 2018; Leifeld et al., 2018). Two studies included in this review examined the relationship between managed burning and charcoal production within upland peatlands (Worrall et al., 2013a; Heinemeyer et al., 2018). Firstly, a low-quality study found that: i) charcoal production "*was approximately 2.6% of the carbon consumed during the fire*"; and, ii) fast burns (<1 minute) at high temperatures (600 ^{o}C) within older stands of *C. vulgaris* (≥15 years old) lead to charcoal additions that increase upland peatland carbon sequestration relative to a no burning policy.

Secondly, a medium quality study (+) by Heinemeyer et al. (2018) carried out peat core analysis using cores taken from three different upland peatland sites managed as grouse moors. This study found that charcoal concentrations (number of charcoal pieces per cm^3 of peat) were positively related to peat bulk density, peat carbon content and thus, carbon accumulation rate (*ibid*). Therefore, the study by Heinemeyer et al. (2018) highlights the potential of managed burning, via charcoal inputs, to increase long-term carbon storage within upland peatland soils. Nevertheless, the results of Heinemeyer et al. (2018) have been debated within the literature (Evans et al., 2019; Heinemeyer et al., 2019b), but, at the same

[9] Ericaceous shrubs, bare peat, mixed vegetation, graminoids or sedges – all assessed using remote sensing.
[10] This is where oxygen is absorbed by carbon molecules and then emitted as carbon dioxide.

time, they are also supported by a study on low-severity fires within a North American peatland (Flanagan et al., 2020).

4.3.6. Upland peatland greenhouse gas budgets

One low-quality study (-) (Clay et al., 2015) and one high-quality study (Heinemeyer et al., 2019c) calculated the effect of managed burning on GHG budgets. Firstly, Clay et al. (2015) estimated[11] GHG budgets across unburnt plots and plots that were burnt one, three, five, six, seven, eight, ten and 11 years before the start of the study. GHG gas budgets were estimated by Clay et al. (2015) using: i) the annual flux of carbon dioxide through photosynthesis; ii) the annual flux of DOC through ecosystem respiration; iii) the annual flux of particulate organic carbon (POC); iv) the annual DOC flux; v) the annual flux of dissolved carbon dioxide; and, vi) the annual methane flux. Clay et al. (2015) found that all the treatment plots were net sources of GHGs, but the most recently burnt plots were smaller sources of carbon than older burns and control plots, which suggests that the "*burning of Calluna-dominated landscapes leads to an 'avoided loss' of carbon*".

Secondly, Heinemeyer et al. (2019c) measured GHG budgets within burnt and unburnt plots over five years (with one-year pre-burn) using: i) NEE; ii) the annual flux of DOC; iii) the annual flux of POC; and, iv) the annual methane flux. The five-year mean suggests that both burnt and unburnt plots were net sources of GHG emissions, but burnt plots showed (expectedly) higher losses over the first five years post-management due to the removal of vegetation biomass (*ibid*).

4.4. Water quality and flow

Six studies investigated the impact of managed burning on water quality and water flow (Johnston, 2012; Brown et al., 2013; Worrall et al., 2013b; Holden et al., 2015; Parry et al., 2015; Heinemeyer et al., 2019c). Five of these studies examined burning impacts directly (Johnston, 2012; Brown et al., 2013; Worrall et al., 2013b; Holden et al., 2015; Heinemeyer et al., 2019c), whereas one study examined burning impacts indirectly by using vegetation composition as a proxy for burning management (Parry et al., 2015).

4.4.1. Water quality

[11] This study estimated (using secondary data) rather than measured some of the elements making up the GHG budget.

Three low-quality studies (-) (Johnston, 2012; Brown et al., 2013; Worrall et al., 2013b), one medium quality study (+) (Parry et al., 2015) and one high-quality study (Heinemeyer et al., 2019c) investigated the impacts of managed burning (either directly or indirectly) on water quality within upland peatlands. Three of these studies used water colour (measured using specific absorbance) as a measure of water quality. Firstly, a plot-scale study by Worrall et al. (2013b) found that managed burning had no effect on water colour within soil pore water or surface run-off within an upland peatland. Secondly, another plot scale study by Heinemeyer et al. (2019c) also found that burning had no effect on soil pore watercolour, but recorded several relationships between water colour and vegetation composition (e.g. increased water colour under increased *Eriophorum* and *Sphagnum* cover, and decreased water colour under increased *C. vulgaris* cover). Thirdly, Parry et al. (2015) investigated the influence of slope and vegetation type (plant functional types) on stream water colour within 119 peatland catchments spanning three drainage basins. Parry et al. (2015) found that different plant functional types[12] had little influence on stream water colour.

Three studies investigated how managed burning influences other aspects of upland peatland water quality. For example, Brown et al. (2013) compared the water quality of five streams draining unburnt peatlands to that of five streams draining burnt peatlands. They found that water within rivers draining burnt peatland had a lower pH and higher concentrations of Si, Mn, Fe, Al, coarse organic matter, and fine organic matter (*ibid*). Similarly, Johnston (2012) compared the water quality of ten streams draining burnt peatlands to that of ten streams draining unburnt peatlands and ten streams draining eroding peatlands. Johnston (2012) found that stream water pH did not differ across catchment types. However, conductivity was higher in streams within burnt and degraded catchments (*ibid*). Finally, Heinemeyer et al. (2019c) found that burning did not affect soil pore water pH.

4.4.2. Water flow

Three low-quality studies (-) (Johnston, 2012; Worrall et al., 2013b; Holden et al., 2015) and one high-quality study (Heinemeyer et al., 2019c) investigated the impacts of managed burning on water flow within upland peatlands. Three of these studies investigated the impact of managed burning on peatland water table depth and/or overland flow (Worrall et al., 2013b; Holden et al., 2015; Heinemeyer et al., 2019c). Worrall et al. (2013b) found that burnt plots had higher water tables than unburnt plots, which they attributed to a reduction in

[12] Ericaceous shrubs, bare peat, mixed vegetation, graminoids or sedges – all assessed using remote sensing.

evapotranspiration that was mediated by the removal of vegetation biomass. Worrall et al. (2013b) also found that burnt plots had a higher frequency of overland flow events than unburnt plots. In contrast to Worrall et al. (2013b), Holden et al. (2015) found that, on average, burnt plots had slightly (~5cm) deeper water tables than unburnt plots. However, when considering the burning age of each burnt plots, this study suggested that water tables recover to a similar level to those found in unburnt plots after >10 years (*ibid*). Holden et al. (2015) also measured overland flow occurrence and, like Worrall et al. (2013b), found that the occurrence of overland flow was greater on burnt than unburnt plots. But the positive effect of burning on overland flow occurrence was not apparent when comparing plots with different burning ages (plots burnt <2 years, 4 years, 7 years and 10+ years since the start of the study) with unburnt plots. In line with Holden et al. (2015), Heinemeyer et al. (2019c) also found that burnt plots had slightly lower water tables than unburnt plots.

Finally, two studies investigated the effect that managed burning has on streamflow by comparing burnt to unburnt upland peatland catchments (Johnston, 2012; Holden et al., 2015). Holden et al. (2015) calculated multiple streamflow metrics for the largest 20% of storm events. Only hydrograph intensity[13] revealed any significant differences in river storm response between burnt and unburnt catchments (it was higher in burnt catchments) (*ibid*). In contrast, Johnston (2012) found no differences in streamflow between burnt, unburnt and eroding peatland catchments.

4.5. Fire ecology

Thirteen studies investigated how differences in burn severity[14] or frequency[15] affect upland peatland ecosystem services (Lee et al., 2013b; Worrall et al., 2013a; Alday et al., 2015; Taylor, 2015; Grau-Andrés et al., 2017; Grau-Andrés et al., 2018; Heinemeyer et al., 2018; Milligan et al., 2018; Noble et al., 2018a; Grau-Andrés et al., 2019a; Grau-Andrés et al., 2019b; Marrs et al., 2019a; Noble et al., 2019a). All 13 studies measured burning impacts directly (*ibid*). Also, six of the studies collected data from the Hard Hill experimental plots (Lee et al., 2013b; Alday et al., 2015; Milligan et al., 2018; Noble et al., 2018a; Marrs et al., 2019a; Noble et al., 2019a).

4.5.1. Burn severity

[13] This is calculated by dividing peak flow values by total stormflow values.
[14] Burn severity relates to the temperatures experienced during a managed burn – the higher the temperatures, the higher the burn severity.
[15] Burn frequency is the number of times an area of interest (e.g. a vegetation plot) has been burnt.

The impact of burn severity was investigated by two low-quality studies (-) (Worrall et al., 2013a; Grau-Andrés et al., 2019a), three medium quality studies (+) (Grau-Andrés et al., 2017; Grau-Andrés et al., 2018; Grau-Andrés et al., 2019b) and two high-quality studies (++) (Taylor, 2015; Noble et al., 2019a). The only consistent finding to emerge across these studies is a positive relationship between *S. capillifolium* damage and burn severity, with lower burn severities causing only very negligible damage to *S. capillifolium* plants relative to unburnt controls (Taylor, 2015; Grau-Andrés et al., 2017; Noble et al., 2019a). Nevertheless, *S. capillifolium* plants are still able to recover even after experiencing a high severity burn (e.g. Clymo and Duckett, 1986; Taylor, 2015; Grau-Andrés et al., 2017)

4.5.2. Burn frequency

One low-quality study (-) (Noble et al., 2018a), two medium quality studies (+) (Lee et al., 2013b; Heinemeyer et al., 2018) and three high-quality studies (++) (Alday et al., 2015; Milligan et al., 2018; Marrs et al., 2019a) measured the effect of burning frequency on upland peatland ecosystem services. The only consistent results are from the five vegetation studies that all analyse data from the Hard Hill experimental plots (Lee et al., 2013b; Alday et al., 2015; Milligan et al., 2018; Noble et al., 2018a; Marrs et al., 2019a). These studies suggest that frequent burning reduces *C. vulgaris* abundance (adult plants and propagules) and increases *Eriophorum* abundance (Lee et al., 2013b; Alday et al., 2015; Milligan et al., 2018; Marrs et al., 2019a). Furthermore, the frequently burnt S plots (burnt every ten years) support similar amounts of *Sphagnum* (mainly *S. capillifolium*) than are found within the L plots (burnt every 20 years), N plots (unburnt since 1954) and R plots (unburnt since 1923) (Milligan et al., 2018; Noble et al., 2018a; Marrs et al., 2019a).

Two further studies investigated the impact of burn frequency on carbon and/or peat accumulation within upland peatland soil profiles (Heinemeyer et al., 2018; Marrs et al., 2019a)

Firstly, Heinemeyer et al. (2018) analysed peat cores taken from three upland peatlands subject to managed burning. Heinemeyer et al. (2018) found that carbon accumulation rates were greater on the most frequently burnt site during 1950–2015 and 1700–1850, which was linked to increases in peat bulk density and charcoal macrofossil concentrations (*ibid*). Secondly, Marrs et al. (2019a) used the Hard Hill experimental plots and found that, while all treatments were accumulating peat and carbon, there was a negative relationship between the number of managed burns a plot has received (S plots = six burns; L plots = three burns, N plots = one burn; R plots = no burns) with peat and carbon accumulation. However, this relationship was driven by the significantly lower peat and carbon accumulation rates recorded in the S plots relative to the R plots (*ibid*). Furthermore, as previously mentioned, the S plots (burnt every ten years) do not represent a realistic rotation length for the local growing conditions in many upland peatlands, which are much more suited to the 20-year rotation of the L plots (Alday et al., 2015).

4.6. Wildfire

No study directly examined the relationship between managed burning and wildfire, but three studies examined this relationship indirectly (Ward et al., 2012; Alday et al., 2015; Heinemeyer et al., 2019c). Two of these studies were conducted using the Hard Hill experimental plots (Ward et al., 2012; Alday et al., 2015)

4.6.1. Fuel loads

Three high-quality studies (++) found that burning reduces heather fuel loads (i.e. dwarf shrub biomass) (Ward et al., 2012; Alday et al., 2015; Heinemeyer et al., 2019c). Two of these studies collected data from the Hard Hill plots (Ward et al., 2012; Alday et al., 2015). The first of these studies by Ward et al. (2012) only used two of the three Hard Hill burning treatment plots: S plots (burnt every ten years) and N plots (unburnt since 1954). Ward et al. (2012) found that dwarf shrub biomass (g m^{-2}) within N plots was between 1,117 and 3476% higher than in S plots (*ibid*).

A second Hard Hill study conducted by Alday et al. (2015) used all three burning treatment plots: S plots (burnt every ten years), L plots (burnt every 20 years) and N plots (unburnt since 1954). The study by Alday et al. (2015) also investigated vegetation biomass within the R plots (plots outside the experimental area unburnt since at least 1923). Alday et al. (2015) found that *C. vulgaris* biomass decreased with increasing time since burn in the main experimental plots: S plots = 60 ± 16 g m^{-2}; L Plots = 672 ± 39 g m^{-2}; and, N plots = 808 ± 16 g m^{-2}. However, *C. vulgaris* biomass within R plots (705 ± 73 g m^{-2}) was intermediate between N and L plots (*ibid*). Similarly, total vegetation biomass increased with increasing time since burn across all the plots investigated: S plots = 1198 ± 165 g m^{-2}; L Plots = 1593 ± 119 g m^{-2}; N plots = 2079 ± 144 g m^{-2}; and, R plots = 2223 ± 201 g m^{-2} (*ibid*).

A third study by Heinemeyer et al. (2019c), which did not use the Hard Hill plots, also found that burning reduces *C. vulgaris* biomass. For example, mean *C. vulgaris* biomass was 97.0 ± 24.9 g within unburnt plots and 6.0 ± 1.4 g within burnt plots two-years post-management (biomass measurements per 660 cm^2).

4.7. Burning extent

Three studies investigated the extent, frequency, practice and/or type of managed burning on upland peatlands (Thacker et al., 2014; Douglas et al., 2015; Allen et al., 2016).

4.7.1. The current extent of managed burning

Three medium quality studies (+) measured the current extent of managed burning on upland peatlands (Thacker et al., 2014; Douglas et al., 2015; Allen et al., 2016). One study measured the extent of managed burning on a single moorland site using management maps and aerial photography[16] (Allen et al., 2016). This study found that an area of 4.16 km^2 was burned at least once over a 22-year-period (1988-2009 broken down into six discrete time periods), which equated to 20% of the entire moorland area or 29% of the"potentially-burnable" area[17] (*ibid*). In addition, over the 22-year-period, the annual amount of burning ranged between 0.5 and 1.6% (0.10 and 0.33 km^2) of the entire moor area or between 0.7 and 2.4% (0.10 and 0.35 km^2) of the potentially-burnable area (*ibid*). Obviously, because this study collected data from a single site (*ibid*), the results cannot be extrapolated across the wider peatland resource.

A second study measured burning extent on upland peatlands by using aerial imagery from upland areas of the UK (images were from the years 2001 to 2010, inclusive) (Douglas et al., 2015). This study found that 278 km^2 of deep peat is currently subject to managed burning in England (*ibid*). According to the extent data provided by the emission inventory of UK peatlands (Evans et al., 2017), the area of peatland subject to burning recorded by Douglas et al. (2015) equates to 8.6% of the total blanket bog (all bog types) or 4.1% of the total peatland area in England. However, the study by Douglas et al. (2015) also found that across England, Scotland and Wales, the mean area of moorland (all soil types) burned per 1 km^2 was higher inside than outside protected areas, such as Special Areas of Conservation and Special Protection Areas (SACs and SPAs, respectively) (*ibid*). Importantly, Douglas et al. (2015) did not validate their methodology by ground-truthing any of the burnt patches digitised using aerial imagery (Davies et al., 2016d; Douglas et al., 2016b). Consequently, the results presented by Douglas et al. (2015) should be treated with caution.

A third study mapped the current (2010) extent of managed burning using aerial imagery that covered 1612 km^2 (80%) of the dwarf shrub-dominated (i.e. *C. vulgaris*

[16] Aerial images were used to validate, digitise and georeference the burn patches determined using estate management maps.
[17] The potentially burnable area is the total moor area minus areas where burning is restricted or not desired.

dominated) upland peatland in England (Thacker et al., 2014). The results of this study suggest that >33 km^2 of new burns are carried out on *C. vulgaris* dominated deep peat soils within the uplands every year (*ibid*). According to Thacker et al. (2014), >33 km^2 per year equates to 3.76% of the total dwarf shrub-dominated upland peatland in England. Conversely, according to the extent data provided by the emission inventory of UK peatlands (Evans et al., 2017), 33 km^2 equates to 1% of the total blanket bog (all bog types) area or 0.5% of the total peatland area in England. However, Thacker et al. (2014) suggest that 33 km^2 is likely to be an imprecise estimate of the annual area burned because 20% of the *C. vulgaris* dominated peatland in the English uplands was unmapped by their study. Furthermore, as with Douglas et al. (2015), Thacker et al. (2014) did not validate their methodology by ground-truthing, which further calls into question the accuracy of their results.

Thacker et al. (2014) also estimated the current (up to 2014 for some sites) extent of managed burning on deep peat within protected areas, such as SACs, SPAs and Sites of Special Scientific Interest (SSSIs). Burning extent on upland peatland ranged from 0-18.8 km^2 per year across all the protected areas studied (*ibid*). However, burning extent was generally below <5 km^2 per year across most sites (*ibid*). However, these results were also not validated by ground-truthing, which means they should be treated with caution.

4.7.2. Temporal changes to the extent of managed burning

Two medium quality studies (+) measured temporal changes in the extent of managed burning on upland peatlands (Thacker et al., 2014; Allen et al., 2016). Allen et al. (2016) measured temporal changes in the extent of managed burning on a single moorland site using estate management maps and aerial photography spanning six sampling periods: i) 1988-1990; ii) 1991-1995; iii) 1996-1999; iv) 2000-2002; v) 2003-2005; and, vi) 2006-2009. They found that the annual extent of managed burning was smaller in 1988-1990 (0.10 km^2; 0.5% of the total area; 0.7% of the potentially burnable area) than in 2006-2009 (0.34 km^2; 1.6% of the total area; 2.4% of the potentially burnable area) (*ibid*). However, the annual extent of managed burning did not increase linearly across all six time periods (*ibid*). As stated previously, the results of Allen et al. (2016) are from a single site. Therefore, Allen et al. (2016) cannot be used to infer temporal increases in burning extent across the wider upland peatland resource.

A second study by Thacker et al. (2014) used a random sample of aerial images covering 2% of the English uplands and found that managed burning on deep peat has increased from 5.3km^2 yr^{-1} in 1945-1959 to 38.9km^2 yr^{-1} in 2010. Nevertheless, and as previously mentioned, the results of Thacker et al. (2014) should be treated with caution because they did not validate their methodology by ground-truthing digitised burning extent.

4.7.3. *Managed burning return intervals*

Two medium quality studies (+) measured managed burning return intervals[18] on upland peatlands (Thacker et al., 2014; Allen et al., 2016). Firstly, Allen et al. (2016) measured managed burning return intervals on a single moorland site using estate management maps and aerial photography. They found that the annual amount of burning ranged between 0.5 and 1.6% (0.10 and 0.33 km^2) of the entire moorland area or between 0.7 and 2.4% (0.10 and 0.35 km^2) of the“potentially-burnable” area (*ibid*). These values translate into burning return intervals of 142–42 and 200–63 years, respectively (*ibid*). However, being from a single site, the results of Allen et al. (2016) cannot be used to infer burning return intervals across the wider peatland resource.

Thacker et al. (2014) used aerial imagery to measure managed burning return intervals across England as well as within a range of SACs, SPAs and Sites of Special Scientific Interest (SSSI) (the aerial images used were from 2006-2014 inclusive). Their data suggest that fire return intervals on deep peat are 26.6 years for the whole of England and between 11.4 to >100 years across individual SACs, SPAs and SSSIs (*ibid*). Nevertheless, caution is required when interpreting the results of Thacker et al. (2014) because they did not validate their methodology by ground-truthing digitised burn areas.

4.7.4. *The frequency of managed burning*

In total, two medium quality studies (+) measured the frequency[19] of managed burning within upland peatlands (Douglas et al., 2015; Allen et al., 2016). Allen et al. (2016) measured temporal changes in the frequency of managed burning on a single moorland site using estate management maps and aerial photography spanning six sampling periods: i) 1988-1990; ii) 1991-1995; iii) 1996-1999; iv) 2000-2002; v) 2003-2005; and, vi) 2006-2009. Overall, 2,561 burns were carried out across the six sampling periods, which equates to a mean of 116 burns per year (*ibid*). The frequency of burns carried out in the most recent sampling period (2006-2009) was higher than during the earliest sampling period (1988-1990), but temporal trends were not analysed using statistical tests (*ibid*). Furthermore, the number of burns carried out during each sampling period fluctuated considerably: 1988-1990 = 61 burns; 1991-1995 =

[18] The length of time, in years, for an entire region of interest to be burnt (Thacker et al., 2014).
[19] The number of burns carried out within a defined time period (e.g. a year).

716 burns; 1996-1999 = 555 burns; 2000-2002 = 498 burns; 2003-2005 = 201 burns; and, 2006-2009 = 530 burns (*ibid*). Importantly, because the results of Allen et al. (2016) are from a single moorland site, they cannot be used to infer burning frequencies across the wider peatland resource.

A second study measured burning frequency on upland peatlands by using aerial imagery from upland areas of the UK (images were from the years 2001 to 2010, inclusive) (Douglas et al., 2015). This study found that "*In England and Scotland, where we had country-wide peat depth data, there was a significant overall increase in annual burn trends*" (*ibid*). However, the raw burn frequency data (for burns on peat) is not provided within the paper or supplementary materials, which means we cannot see the variability of burning frequency across survey years. Also, Douglas et al. (2015) did not validate their methodology by ground-truthing any of the burn patches digitised using aerial imagery (Davies et al., 2016d; Douglas et al., 2016b). Consequently, the results presented by Douglas et al. (2015) should be treated with caution.

4.7.5. The size of management burning patches

One medium quality study (+) measured the size of managed burning patches on upland peatlands (Allen et al., 2016). This study measured the size of managed burning patches on a single moorland site using estate management maps and aerial photography (the latter were used to validate, digitise and georeference the burn patches determined using estate management maps) spanning six sampling periods: i) 1988-1990; ii) 1991-1995; iii) 1996-1999; iv) 2000-2002; v) 2003-2005; and, vi) 2006-2009. Across the entire study period, the mean burn patch size was 2098 ± 67 m^2 and burn patch sizes ranged from 33-110,000 m^2 (*ibid*). However, most of the burn patches throughout the study period were between 501 and 1000 m^2 (*ibid*). It is also worth noting that burn patch size varied considerably: 1988-1990 = 5080 ± 1780 m^2; 1991-1995 = 1800 ± 80 m^2; 1996-1999 = 1530 ± 85 m^2; 2000-2002 = 2060 ± 94 m^2; 2003-2005 = 2640 ± 284 m^2; and, 2006-2009 = 2580 ± 141 m^2 (*ibid*). However, results from this single site tell us very little about the size of burning patches across the wider peatland resource.

4.8. Soils

Ten studies investigated the impact of managed burning on peat soils (Rosenburgh et al., 2013; Vane et al., 2013; Brown et al., 2015b; Clay et al., 2015; Grau-Andrés et al., 2018;

Grau-Andrés et al., 2019b; Heinemeyer et al., 2019a; Heinemeyer et al., 2019c; Morton and Heinemeyer, 2019; Noble et al., 2019a). All ten of these studies measured burning impacts directly (as opposed to using proxies for managed burning, such as vegetation height or composition).

4.8.1. Post-fire soil temperatures

One high-quality (+) study (Heinemeyer et al., 2019c), two medium quality (+) studies (Grau-Andrés et al., 2018; Grau-Andrés et al., 2019b) and one low quality (-) study (Brown et al., 2015b) investigated the impact of managed burning on post-fire soil temperatures. Three of these studies found that, compared to unburnt or not recently burnt plots, post-fire soil temperatures were higher in burnt plots (Brown et al., 2015b; Grau-Andrés et al., 2018; Grau-Andrés et al., 2019b). However, in general, the mean differences in post-fire soil temperatures (at various depths) between burnt/recently burnt and unburnt/not recently burnt plots were generally <1^{o}C (*ibid*). Furthermore, Grau-Andrés et al. (2018) and Grau-Andrés et al. (2019b) found that burning only minimally increased post-fire soil temperatures during the summer months, but not in Spring or Autumn. Grau-Andrés et al. (2018) also found that, relative to unburnt plots, burning did not affect soil accumulated heat, which is "*the daily growing degree hours for each plot, i.e. the sum of ^{o}C above 4^{o}C, the minimum temperature for plant growth, in each hour during a day*". Finally, Heinemeyer et al. (2019c) found that mean post-fire soil temperatures were similar within burnt and unburnt plots. However, burnt plots had larger soil temperature ranges (increased maxima and minima) and slightly higher maximum soil temperatures (*ibid*).

4.8.2. Soil compaction

Three high-quality studies (++) (Heinemeyer et al., 2019a; Morton and Heinemeyer, 2019; Noble et al., 2019a) and one low-quality study (-) (Rosenburgh et al., 2013) examined the impact of burning on soil compaction. Heinemeyer et al. (2019a) found no differences in soil compaction between unburnt and burnt treatments, which was measured using soil bulk density and peat depth pre and post-management. Simalarly, Rosenburgh et al. (2013) found that time since burn had no effect of soil compaction, which was measured using soil bulk density.

Conversely, Morton and Heinemeyer (2019) found that, relative to an unburnt control, burning reduced peat height after two years post-management (Morton and Heinemeyer, 2019). However, the interaction between site and management recorded in the study suggested that the negative effect of burning on peat height was driven by the results from one of the three sites used, most likely in relation to slope position and peat compaction (shrinkage) due to lower water tables (*ibid*). Finally, Noble et al. (2019a) found that burning led to an increase in peat bulk density after five months post-treatment, but only when unburnt plots were compared to "high-temperature" plots[20]. Indeed, there were no differences in post-treatment peat bulk density between "low temperature" plots[21] and unburnt plots. Importantly, however, increased peat bulk density has been linked to increased charcoal inputs (Heinemeyer et al., 2018).

4.8.3. Soil moisture

One medium quality study (+) (Grau-Andrés et al., 2019b) and two high-quality studies (++) (Heinemeyer et al., 2019c; Noble et al., 2019a) examined the impact of burning on post-fire soil moisture. Grau-Andrés et al. (2019b) measured soil moisture in the top 6 cm of the peat surface and found that burning did not affect post-fire soil moisture compared to unburnt controls. Conversely, two additional studies measured soil moisture in the top 6-8 cm of the peat surface and found that, relative to an unburnt control, burning decreased post-fire soil moisture (Heinemeyer et al., 2019c; Noble et al., 2019a).

4.8.4. Soil chemistry

Two low-quality studies (-) investigated the impact of burning on soil chemistry (Rosenburgh et al., 2013; Vane et al., 2013). One study examined the concentrations of polycyclic aromatic hydrocarbons (PAH) added to the peat surface after vegetation burning (Vane et al., 2013). This study found that, compared to unburnt vegetation, burnt surface ash had much higher concentrations of the 18 PAH studied, which suggests vegetation burning on upland peatlands leads to the net addition of PAH to the soil surface (*ibid*). Nevertheless, "*there was no evidence to suggest that the amounts of PAH accumulating from moorland burning are harmful to humans since these are below the generic assessment criteria for soils*" (*ibid*).

The other study investigated how time since burn affects the concentration of multiple chemical properties within peat soils (Rosenburgh et al., 2013). Overall, time since burn did not affect most of the soil chemical properties measured within this study (*ibid*). However, the study did record a negative relationship between time since burning and soil C:N (carbon

[20] Plots where fire temperatures were between 324-538^{o}C
[21] Plots where fire temperatures were between 33-137^{o}C

to nitrogen) ratios, which suggests that peatlands become gradually more saturated with nitrogen as time since burning increases (*ibid*).

4.8.5. Upland peatland soil erosion

One low-quality study (-) investigated the impact of time since burn and soil erosion (Clay et al., 2015). This study used erosion pins[22] and found that more recently burnt plots[23] lost peat, whereas plots burnt seven or more years before the start of the study actively accumulated peat (*ibid*). However, erosion pins inserted into the top 200mm of the peat surface are not a reliable way to measure soil erosion. For example, the peat surface is likely to have moved during the study period due to natural soil contraction and expansion (e.g. wet-dry cycles) (Morton and Heinemeyer, 2019), rather than peat erosion or accumulation.

[22] Pins were 600mm long, 2mm diameter stainless steel rods inserted 200mm into the peat surface.
[23] Plots burnt one, three and six years before the start of the study.

5. Evidence summary statements

The studies included within this review use a diverse range of experimental designs, predictor variables and measurements. Such heterogeneity prevents the use of meta-analysis to objectively summarise the impacts of managed burning on peatland ecosystem services (Haidich, 2010; Shorten and Shorten, 2013). Consequently, the evidence compiled herein has been summarised using a narrative synthesis approach (Grant and Booth, 2009). As such, the following evidence statements are subjective and should, therefore, be considered as highly uncertain. Nevertheless, the methods, rationale and supporting data behind these evidence statements are fully transparent. Thus, even if other researchers disagree with the evidence summaries provided below, they will understand how they were formed.

5.1. Flora

5.1.1. Vegetation diversity

Quantity and quality of the evidence assessed for this topic: Seven studies examined the effect of burning on vegetation species richness or diversity – two low-quality studies (-), two medium quality studies (+) and three high-quality studies (++). One low-quality study (-) investigated the impact of managed burning on *Sphagnum* species richness.

Is the direction of the evidence consistent? No, for vegetation species richness or diversity. NA, for *Sphagnum* species richness – cannot assess evidence consistency using a single study.

If so, what is the direction of the evidence? NA.

5.1.2. Vegetation structure

Quantity and quality of the evidence assessed for this topic: Four studies examined burning impacts on the microtopography of the peatland surface – one low-quality study (-), one medium quality study (+) and two high-quality studies (++). Seven studies examined the impacts of managed burning on the structure of the vegetation canopy (usually heather height) – two low-quality studies (-), three medium quality studies (+) and two high-quality studies (++).

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"The new review concludes that burning has a neutral effect on Sphagnum abundance and initial damage done by low severity fire to Sphagnum capillifolium almost fully recovers within three years..."

Is the direction of the evidence consistent? No, for burning impacts on surface microtopography. Yes, for burning impacts on vegetation canopy height.

If so, what is the direction of the evidence? Unsurprisingly, managed burning leads to a short-term reduction in canopy height, but canopy height then increases with time since burn.

5.1.3. Sphagnum species

Quantity and quality of the evidence assessed for this topic: Ten studies examined the impact of burning on *Sphagnum* abundance (primarily, *S. capillifolium* abundance) – five low-quality studies (-), two medium studies (+) and three high-quality studies (++). Three studies examined the temperature-induced *S. capillifolium* damage during managed burning – one medium quality study (+) and two high-quality studies (++). One medium quality study (+) examined the impact of burning on the proportion of *Sphagnum* propagules in the surface peat layers.

Is the direction of the evidence consistent? Yes, for S. *capillifolium* abundance. Yes, temperature-induced *S. capillifolium* damage. NA, for the proportion of *Sphagnum* propagules in the surface peat layers – cannot assess evidence consistency using a single study.

If so, what is the direction of the evidence? Managed burning seems to have a neutral impact on *S. capillifolium* abundance. However, managed burning does lead to short-term damage of *S. capillifolium* plants, with affected plants recovering within the space of three years (two out of three studies). Although, damage to *S. capillifolium* plants is likely to be minimal to absent when managed burns do not exceed 137 ^{o}C at the soil or vegetation surface.

5.1.4. Eriophorum species

Quantity and quality of the evidence assessed for this topic: Eleven studies – four low-quality (-), two medium quality studies (+) and five high-quality studies (++).

Is the direction of the evidence consistent? No.

If so, what is the direction of the evidence? NA.

5.1.5. Calluna vulgaris

Quantity and quality of the evidence assessed for this topic: Fourteen studies examined the impact of burning on *C. vulgaris* abundance – four low-quality studies (-), four medium quality studies (+) and six high-quality studies (++). One medium quality study (+) examined the impact of burning on the proportion of *C. vulgaris* propagules in the surface peat and litter layers. One high-quality study (++) examined the impact of burning on *C. vulgaris* germination.

Is the direction of the evidence consistent? Yes, for *C. vulgaris* abundance. NA, for the proportion of *C. vulgaris* propagules – cannot assess evidence consistency using a single study. NA, for *C. vulgaris* germination – cannot assess evidence consistency using a single study.

If so, what is the direction of the evidence? Frequent managed burning (i.e. rotational burning) reduces *C. vulgaris* abundance, but *C. vulgaris* increases and eventually becomes dominant within areas left unburnt for long periods (e.g. it has remained dominant for 90+ years within the Hard Hill Experiment unburnt reference plots: Milligan et al., 2018).

5.1.6. Bare ground

Quantity and quality of the evidence assessed for this topic: Six studies – two low-quality studies (-), three medium quality studies (+) and one high-quality study (++).

Is the direction of the evidence consistent? Yes.

If so, what is the direction of the evidence? Burning leads to the small-scale increase in bare ground, but this seems to be a transient effect (lasting four to ten years).

5.1.7. Paleoecology studies

Quantity and quality of the evidence assessed for this topic: Nine studies explored the relationship between fire (wildfire or managed burning) and *Sphagnum* occurrence down through the peat profile – eight low-quality studies (-) and one medium quality study (+). Nine studies explored the relationship between fire (wildfire or managed burning) and *C. vulgaris* occurrence down through the peat profile – seven low-quality studies (-) and two medium quality studies (+). Six studies explored the relationship between fire (wildfire or managed burning) and *Eriophorum* occurrence down through the peat profile – five low-quality studies (-) and one medium quality study (+).

Is the direction of the evidence consistent? Yes, for *Sphagnum*. No, for *Eriophorum* and *C. vulgaris*.

If so, what is the direction of the evidence? In general, increased evidence of fire within the peat profile (i.e. the abundance of charcoal macrofossils) is coincident with declines in *Sphagnum* abundance. However, it is important to note that none of the paleoecology studies included in this review tested the relationship between fire occurrence and *Sphagnum* abundance. Nor did they consider other drivers of vegetation change, such as grazing (wild or domesticated), drainage, climate, carbon dioxide levels (in terms of photosynthesis) or atmospheric pollution (e.g. sulphur or nitrogen). Thus, the paleoecology studies included in this review should be considered as circumstantial evidence. Another issue with the paleoecology studies included in this review is the lack of spatial replication. Indeed, half of the studies only explored relationships using a single master peat core from within a single site (Blundell and Holden, 2015; McCarroll et al., 2016b; McCarroll et al., 2016a; Swindles et al., 2016; McCarroll et al., 2017). The lack of spatial replication means that the results cannot be generalised across the wider peatland resource. In short, while paleoecology studies provide valuable insights into historical vegetation change within UK peatlands, any results from such studies should be considered as potential hypotheses to be tested with more robust methods that are better able to ascribe causation (i.e. randomised controlled experiments).

5.2. Fauna

5.2.1. Birds

Quantity and quality of the evidence assessed for this topic: Twelve studies overall – two low-quality studies (-) and ten medium quality studies (+). Six medium quality studies (+) investigated burning impacts (either directly or indirectly) on *P. apricaria* populations.

Is the direction of the evidence consistent? Yes, but only for *P. apricaria*.

If so, what is the direction of the evidence? By promoting areas with shorter and/or more varied vegetation structure across a moorland, managed burning seems to have a positive effect on *P. apricaria* populations within upland peatlands. However, managed burning often coincides with predator control in many upland areas, which means we do not know the relative importance of managed burning in promoting *P. apricaria* populations (but see Littlewood et al., 2019).

5.2.2. Aquatic invertebrates

Quantity and quality of the evidence assessed for this topic: Three low-quality studies (-).

Is the direction of the evidence consistent? No.

If so, what is the direction of the evidence? NA.

5.2.3. Terrestrial invertebrates

Quantity and quality of the evidence assessed for this topic: One high-quality study (++).

Is the direction of the evidence consistent? NA – Cannot assess evidence consistency using a single study.

If so, what is the direction of the evidence? NA.

5.2.4. Soil microorganisms

Quantity and quality of the evidence assessed for this topic: Two studies – one low-quality study (-) and one high-quality study (++).

Is the direction of the evidence consistent? No. While both studies show that burning leads to changes in microorganism communities found within peatland soils, each study investigates a different taxon.

If so, what is the direction of the evidence? NA.

5.3. Carbon sequestration and greenhouse gas emissions

5.3.1. Carbon and peat accumulation within upland peatland soil profiles

Quantity and quality of the evidence assessed for this topic: Two studies investigated the impact of managed burning on carbon accumulation within upland peatland soil profiles –

one medium quality study (+) and one high-quality study (++). One high-quality study (++) investigated the impact of managed burning on peat accumulation within upland peatland soil profiles.

Is the direction of the evidence consistent? Yes, for carbon accumulation. NA, for peat accumulation – cannot assess evidence consistency using a single study.

If so, what is the direction of the evidence? Both studies suggest that upland peatlands subject to managed burning accumulate, rather than lose, carbon within the peat profile (Heinemeyer et al., 2018; Marrs et al., 2019a). However, it is important to note that the findings of Heinemeyer et al. (2018) and Marrs et al. (2019a) have been debated within the scientific literature (Baird et al., 2019; Evans et al., 2019; Heinemeyer et al., 2019b; Marrs et al., 2019b). Nevertheless, the general finding that flat, fully vegetated and wet upland peatlands (like those studied by Marrs et al., 2019a and Heinemeyer et al., 2018) subject to managed burning accumulate (rather than lose) carbon is supported by previous work (Garnett et al., 2000). Furthermore, the work of Marrs et al. (2019a) suggests that flat and wet areas of blanket bog under longer rotations (e.g. 20 years) accumulate peat and carbon at a similar rate to areas that have remained unburnt for between ~60 to 90 years.

There is a potential caveat that should be considered when interpreting the results of the near-surface[24] carbon accumulation assessments of Heinemeyer et al. (2018) and Marrs et al. (2019a). As Heinemeyer et al. (2018) acknowledge, near-surface carbon accumulation assessments often show rapid carbon accumulation due to lower decomposition rates at the peat surface, but the same peat section could be losing carbon from the opposite (bottom) end of the profile (as shown in the modelling study by Young et al., 2019). Therefore, researchers should ideally assess carbon accumulation throughout the entire peat core (*ibid*). Alternatively, when only near-surface peat core sections are used, researchers should consider site conditions when interpreting their findings (*ibid*). For example, sites affected by deep drainage ditches or that have become very dry for other reasons, are likely to be losing carbon from lower down the peat profile (*ibid*). In such scenarios, one should not relate near-surface carbon accumulation rates to the rest of the peat body (*ibid*). However, any such carbon losses should be indicated by a sharp decline in organic carbon content, which neither Heinemeyer et al. (2018) or Marrs et al. (2019a) observed. Furthermore, near-surface carbon

[24] Near-surface means near the top of the peat profile.

accumulation data taken from wet peatland sites (and with no indication for deep C loss) *can* be generalised to the entire peat body because such places are unlikely to be losing carbon from the deeper peat layers. Consequently, the flat, fully vegetated and wet upland peatland areas studied by Heinemeyer et al. (2018) and Marrs et al. (2019a) are unlikely to be losing considerable amounts carbon from the base of the peat profile. However, future work must verify such an assertion.

5.3.2. Upland peatland carbon fluxes

Quantity and quality of the evidence assessed for this topic: Seven studies – one low-quality study (-), two medium quality studies (+) and four high-quality studies (++).

Is the direction of the evidence consistent? No.

If so, what is the direction of the evidence? NA

5.3.3. Upland peatland methane fluxes

Quantity and quality of the evidence assessed for this topic: Five studies – one medium quality study (+) and four high-quality studies (++).

Is the direction of the evidence consistent? No.

If so, what is the direction of the evidence? NA.

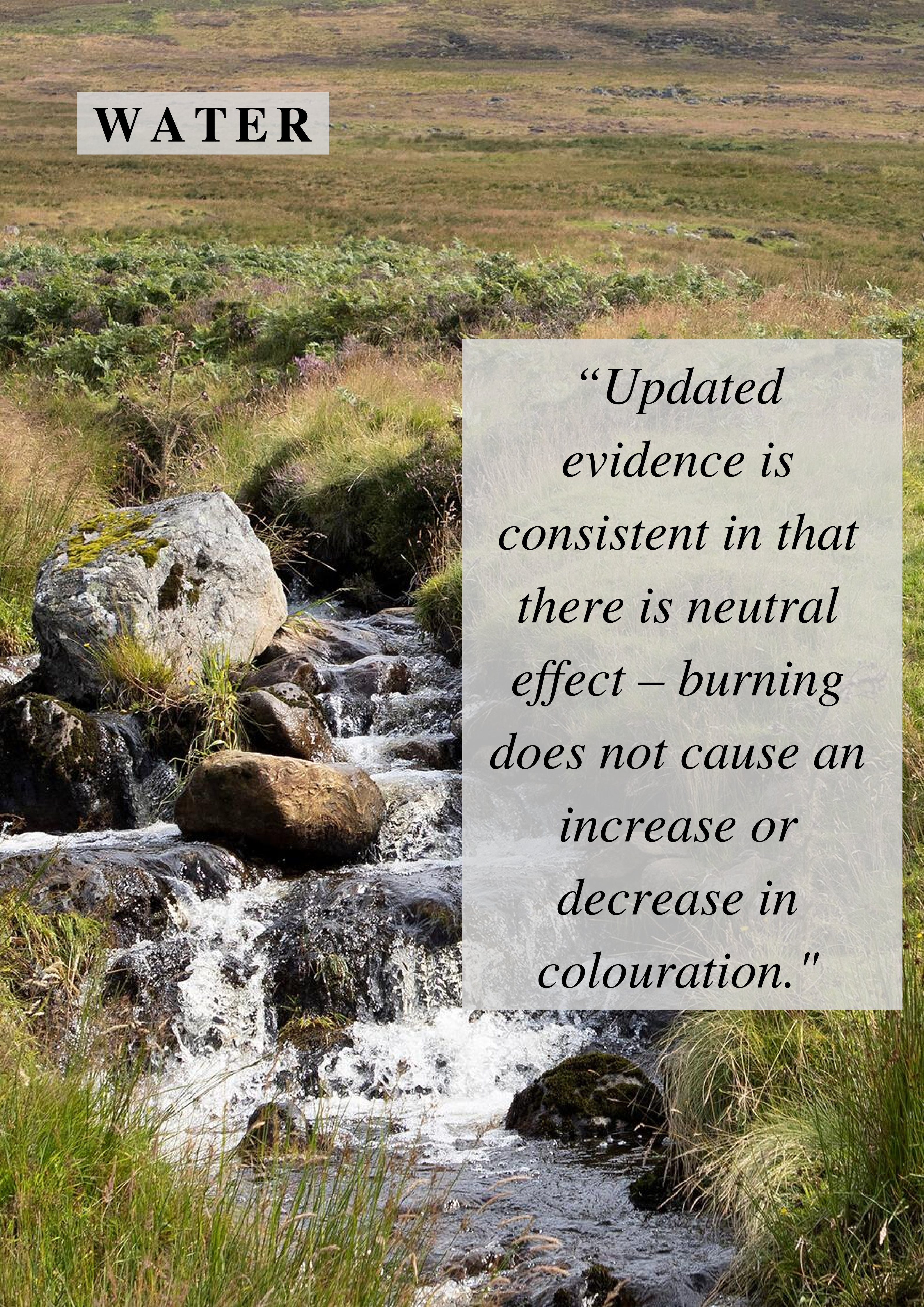
5.3.4. Upland peatland dissolved organic carbon fluxes

Quantity and quality of the evidence assessed for this topic: Five studies – one low-quality study, two medium-quality studies (+) and two high-quality studies (++).

Is the direction of the evidence consistent? Yes.

If so, what is the direction of the evidence? Four out of the five studies suggest that managed burning has no impact on dissolved organic carbon fluxes in upland peatlands (either directly or indirectly via changes to vegetation composition).

5.3.5. Charcoal production



WATER

“Updated evidence is consistent in that there is neutral effect – burning does not cause an increase or decrease in colouration."

Quantity and quality of the evidence assessed for this topic: Two studies – one low-quality study (-) and one medium quality study (+).

Is the direction of the evidence consistent? Yes.

If so, what is the direction of the evidence? Both studies suggest that by adding charcoal to the peat profile, managed burning may lead to long-term carbon storage benefits.

5.3.6. Upland peatland greenhouse gas budgets

Quantity and quality of the evidence assessed for this topic: One low-quality study (-) and one high-quality study (++).

Is the direction of the evidence consistent? Yes.

If so, what is the direction of the evidence? Both burnt and unburnt plots are net sources (rather than sinks) of GHG emissions. However, one study (++) suggests that burnt plots are greater sources of GHG during the first four post-management years. In contrast, a second study (-) suggests that the more recently burned areas are smaller sources of GHGs than older burns. A major issue with both studies is the limited study length, which is much less than a complete burn rotation (or, even better, several burning rotations).

5.4. Water quality and flow

5.4.1. Water quality

Quantity and quality of the evidence assessed for this topic: Three studies examined the impact of managed burning on water colour (measured at different scales and locations across studies) – one low-quality study (-), one medium quality study (+) and one high-quality study (++). Three studies measured the impact of burning on water pH (within either soil water or stream water) – two low-quality studies (-) and one high-quality study (++).

Is the direction of the evidence consistent? Yes, for water colour. No, for pH.

If so, what is the direction of the evidence? Managed burning has no impact on water colour.

5.4.2. Water flow

Quantity and quality of the evidence assessed for this topic: Two low-quality (-) studies investigated the impact of managed burning on overland flow. Two low-quality (-) studies investigated the impact of managed burning on streamflow Three studies investigated the impact of managed burning on water table depth - two low-quality studies (-) and one high-quality study (++).

Is the direction of the evidence consistent? Yes, for overland flow. No, for streamflow. No, for water table depth.

If so, what is the direction of the evidence? Managed burning leads to an increase in overland flow on upland peatlands. However, these findings are from two low-quality studies with serious methodological flaws (e.g. pseudoreplication and/or significant confounding as shown by Ashby and Heinemeyer, 2019a; Ashby and Heinemeyer, 2019b). Also, it is not evident that the increases in overland flow mediated by managed burning lead to increased flood risk. For example, the impact of managed burning on streamflow is unclear (Johnston, 2012; Holden et al., 2015).

5.5. Fire ecology

5.5.1. Burn severity

Quantity and quality of the evidence assessed for this topic: Seven studies investigated the impact of burn severity on peatland ecosystem services – two low-quality studies (-), three medium quality studies (+) and two high-quality studies (++). Specifically, three studies investigated the impact of burn severity on *S. capillifolium* damage – one medium quality study (+) and two high-quality studies (++).

Is the direction of the evidence consistent? Yes, for the relationship between burn severity and *S. capillifolium* damage.

If so, what is the direction of the evidence? There is a positive relationship between burn severity and *S. capillifolium* damage, with lower burn severities causing minimal damage to *S. capillifolium* plants relative to unburnt controls. Nevertheless, *S. capillifolium* plants are still able to recover after experiencing high severity burns (within the space of three years).

5.5.2. Burn frequency

Quantity and quality of the evidence assessed for this topic: Four studies examined the relationship between burn frequency and *C. vulgaris* abundance – three high-quality studies (++) and one medium quality study (+). Two high-quality studies (++) examined the relationship between burn frequency and *Eriophorum* abundance. Three high-quality studies (++) examined the relationship between burn frequency and *Sphagnum* (mainly *S. capillifolium*) abundance.

Is the direction of the evidence consistent? Yes, for *C. vulgaris, Eriophorum* and *Sphagnum* (mainly *S. capillifolium*) abundance.

If so, what is the direction of the evidence? There is a negative relationship between burning frequency and *C. vulgaris* abundance (adult plants and propagules), and a positive relationship between burning frequency and *Eriophorum* abundance. Also, frequently burnt plots (burnt every ten and 20 years) can support similar amounts of *Sphagnum* (mainly *S. capillifolium*) than plots left unburnt for 60-90 years. It is important to note that these findings come from a single experiment: The Hard Hill experimental plots.

5.6. Wildfire

5.6.1. Fuel loads

Quantity and quality of the evidence assessed for this topic: Three high-quality (++) studies.

Is the direction of the evidence consistent? Yes.

If so, what is the direction of the evidence? Frequent managed burning significantly reduces fuel loads on upland peatlands. However, two of the three studies measuring fuel loads collected data from a single experimental site in the Northern Pennines: The Hard Hill experimental plots. Nevertheless, several additional studies have shown that the cessation in burning management also leads to significant increases in the percentage cover of dwarf shrubs (mainly *C. vulgaris*) on upland peatlands (Lee et al., 2013a; Milligan et al., 2018; Whitehead and Baines, 2018; Grau-Andrés et al., 2019a; Noble et al., 2019b); and, percentage cover is closely correlated with vegetation biomass (Muukkonen et al., 2006; Axmanová et al., 2012).

5.7. Burning extent

5.7.1. The current extent of managed burning

Quantity and quality of the evidence assessed for this topic: Three medium quality (+) studies.

Is the direction of the evidence consistent? No – burning extent is variable across studies.

If so, what is the direction of the evidence? NA

5.7.2. Temporal changes to the extent of managed burning

Quantity and quality of the evidence assessed for this topic: Two medium quality studies (+).

Is the direction of the evidence consistent? Yes.

If so, what is the direction of the evidence? Both studies suggest that burning extent has increased in recent decades (at least up to 2009/2010). However, one study was from a single moorland site, and the second study did not validate the method used to calculate burning extent and only assessed 2% of the English uplands. Moreover, both studies are out of date because their last sampling point was over ten years ago (Thacker et al., 2014; Allen et al., 2016) – burning extent may have changed since then.

5.7.3. Managed burning return intervals

Quantity and quality of the evidence assessed for this topic: Two medium quality studies (+).

Is the direction of the evidence consistent? No – burning return intervals are variable across studies and sites. This probably reflects differences in *Calluna vulgaris* growth rates across sites with different environmental conditions (e.g. Santana et al., 2015).

If so, what is the direction of the evidence? NA

5.7.4. The frequency of managed burning

Quantity and quality of the evidence assessed for this topic: Two medium quality studies (+)

Is the direction of the evidence consistent? Yes.

If so, what is the direction of the evidence? Both studies suggest that the number of burns has increased between 1988-2009 (Allen et al., 2016) and 2001-2010 (Douglas et al., 2015). However, one study was from a single moorland site, and both studies are out of date because their last sampling point was over ten years ago (Douglas et al., 2015; Allen et al., 2016) – the trend in burning frequency may have changed since then. Also, the burning frequencies recorded by Allen et al. (2016) were highly variable across sampling periods.

5.7.5. The size of management burning patches

Quantity and quality of the evidence assessed for this topic: One medium quality study (+)

Is the direction of the evidence consistent? NA – Cannot assess evidence consistency using a single study.

If so, what is the direction of the evidence? NA

5.8. Soils

5.8.1. Post-fire soil temperatures

Quantity and quality of the evidence assessed for this topic: One high-quality study (++), two medium quality studies (+) and one low-quality study (-).

Is the direction of the evidence consistent across studies? Yes

If so, what is the direction of the evidence? When considering the impact across all seasons examined within each study[25], managed burning seems to have a neutral impact on post-fire soil temperatures.

5.8.2. Soil compaction

Quantity and quality of the evidence assessed for this topic: Three high-quality studies (++) and one low-quality study (-).

Is the direction of the evidence consistent? No.

[25] For example, Grau-Andrés et al. (2019b) found no differences in post-fire soil temperatures during two out of the three seasons investigated.

If so, what is the direction of the evidence? NA.

5.8.3. Soil moisture

Quantity and quality of the evidence assessed for this topic: Two high-quality studies (++) and one medium quality study (+).

Is the direction of the evidence consistent? No.

If so, what is the direction of the evidence? NA.

5.8.4. Soil chemistry

Quantity and quality of the evidence assessed for this topic: Two low-quality studies (-).

Is the direction of the evidence consistent? No. While the two studies show that burning leads to changes in the chemical properties within peatland soils, each study investigates a different range of chemical properties.

If consistent, what is the direction of the evidence? NA.

5.8.5. Upland peatland soil erosion

Quantity and quality of the evidence assessed for this topic: One low-quality study (-).

Is the direction of the evidence consistent? NA – cannot assess evidence consistency using a single study.

If so, what is the direction of the evidence? NA.

6. Research recommendations

Before providing research recommendations for each review sub-question, the list below outlines a series of generic research recommendations that are informed by the critical appraisal of the evidence included in this review. With this in mind, future studies investigating the impact of managed burning on upland peatland ecosystems should consider:

- Randomly allocating treatment or survey plots.
- Including an unburnt or not recently burnt control.
- Using an experimental, rather than correlative, study design.
- Collecting data from multiple peatland sites, with each site containing treatment replicates to avoid the confounding of burning management with study site (and other environmental variables).
- Collecting data from across more than one burning rotation and for at least three different years within a burning rotation.
- Collecting baseline data.
- Examining the effect of managed burning at both the plot and catchment scale.
- Investigating different burn rotation lengths and burn severities.

The above research recommendations provide a framework to investigate burning impacts on upland peatlands using a robust[26] and real-world[27] approach that is largely absent within the current evidence base. Indeed, just one of the studies included in this review has adopted such an approach (Heinemeyer et al., 2019c), but this project has only been running for ten years and does not compare burning to an unburnt control at the catchment scale (catchment-scale comparisons are made between burning and mowing). The remaining studies in this review

[26] An experimental approach that allows you to ascribe causation, e.g., a randomised controlled before-and-after trial.
[27] One which examines burning in the same way it is applied by upland land managers, e.g., every year, multiple patches of varying size (but usually ~2500 m^2) are burnt on rotation across an extensive area of moorland using rotations that are suited to the local environmental (i.e. growing) conditions.

generally measured burning impacts using a plot-scale approach in which burning impacts were measured for only a short period post-burn (<4 years). As a result, the evidence base largely provides data about the short-term impacts of managed burning on upland peatland ecosystem services.

6.1. Flora

6.1.1. Vegetation diversity

The number and geographical distribution of studies investigating burning impacts on peatland vegetation diversity are still limited. For example, studies are mostly conducted in northern England, with 40% of UK studies using data from the Hard Hill experimental plots. Therefore, future studies should be conducted across a wider geographical area.

6.1.2. Vegetation structure

The impact of managed burning on peatland surface microtopography was investigated using a short-term approach whereby measurements were taken for no more than a couple of years at the start of a burning rotation (Noble et al., 2018a; Heinemeyer et al., 2019a; Noble et al., 2019a; Noble et al., 2019b). Therefore, future studies should document how peatland surface microtopography changes across the entire burning rotation relative to unburnt control areas. Alongside this, we also need to know how changes to peatland surface microtopography influence important ecological parameters such as carbon and peat accumulation, flood prevention, water quality improvement and wildfire mitigation.

It is self-evident that burning initially reduces the height of the vegetation canopy and that canopy height recovers as time since burning increases. Nevertheless, there is very little research into the wider implications of this relationship. For example, by removing the shade and competition caused by a dense *Calluna vulgaris* canopy, managed burning may provide more conducive conditions for *Sphagnum* growth (e.g. Gunnarsson et al., 2002; Benscoter and Vitt, 2008). Furthermore, by reducing fuel loads, managed burning may also play a role in wildfire prevention and mitigation (Santana et al., 2015; Santana et al., 2016; Santana and Marrs, 2016). Both aspects require urgent research attention.

6.1.3. Sphagnum species

Most of the studies included here and within Glaves et al. (2013) focus on *S. capillifolium*, which is probably because other *Sphagnum* species are less frequent within many upland peatland sites. Consequently, even if other *Sphagnum* species are recorded, there is usually insufficient data to carry out robust statistical analyses. Nevertheless, we still need to know how managed burning effects the full range of *Sphagnum* species found within upland peatlands across the UK. Therefore, future studies should attempt to address this important research gap.

Another issue is that ~40% of the *Sphagnum* studies use data collected from the Hard Hill experimental plots, which suggests future studies should try to collect data from different sites to reduce the geographical bias of the evidence base. Finally, none of the studies investigating the effect of fire damage on *Sphagnum* plants collected data for more than three years. This represents a significant research gap that will inform us of whether fire-induced heat damage of *Sphagnum* plants leads to long-term ecological consequences (this seems unlikely given that burning does not reduce the abundance of *Sphagnum* spp.).

Before we can consider the wider implications of managed burning impacts on *Sphagnum* spp., we also need robust experimental data on the ecological functions of *Sphagnum* within upland peatlands. For example, experimental evidence about its contribution to peat and carbon accumulation, water storage capacity and flood mitigation, water quality, and wildfire prevention and mitigation. Indeed, it has long been stated within the literature that *Sphagnum* species have a positive effect on peat and carbon accumulation, but this is based on circumstantial (rather than causal) evidence from paleoecology studies (see Shepherd et al., 2013; Gillingham et al., 2016 and references therein).

6.1.4. Eriophorum species

Before we can consider the wider implications of burning impacts on *Eriophorum* species, we need robust experimental data on the ecological functions that *Eriophorum* species provide within upland peatlands. For example, the contribution they make to peat and carbon accumulation, methane emissions, water storage capacity and flood mitigation, water quality improvements, and wildfire prevention and mitigation. Again, as with *Sphagnum*, it has long been stated within the literature that *Eriophorum* species have a positive effect on peat and carbon accumulation, but this is based on circumstantial (rather than causal) evidence from peat record (see Shepherd et al., 2013; Gillingham et al., 2016 and references therein).

6.1.5. Calluna vulgaris

Before we can consider the wider implications of managed burning impacts on *C. vulgaris* abundance, we need robust experimental data on the ecological functions of *C. vulgaris* within upland peatlands. For example, its contribution to peat and carbon accumulation, methane emissions, water storage capacity and flood mitigation, water quality, and wildfire prevention and mitigation. The role of *C. vulgaris* abundance in wildfire prevention and mitigation is a particularly urgent research priority given its flammability (Davies and Legg, 2011; Santana and Marrs, 2016) and the predicted rise in moorland wildfires due to warmer and drier summers (Albertson et al., 2009; Albertson et al., 2010).

6.1.6. Bare ground

Only two studies included in this review examined the temporal changes to bare ground after a managed burn has been applied (Heinemeyer et al., 2019c; Noble et al., 2019b). Future studies should address this research gap. What would be particularly useful would be information on how long it takes for the small post-burn patches of bare ground to revegetate, and how this varies with changes in climate, water table depth, peat depth, fire severity, fire frequency, burn rotation length and vegetation community. Also, and as mentioned for other aspects of peatland vegetation, before we can consider the wider implications of these findings, we need robust experimental data on how the small-scale and transient creation of bare ground affects ecological functions within upland peatlands (e.g. peat and carbon accumulation, methane emissions, water storage capacity and flood mitigation, water quality improvements, wildfire prevention and mitigation, and biodiversity). We should also consider that the creation of small patches of bare ground may provide benefits, such as providing micro-habitats for invertebrates (Cameron and Leather, 2012).

6.1.7. Paleoecology studies

Before any valid conclusions or lessons can be drawn from paleoecology studies on upland peatlands, we really need a greater number of studies which: i) are multi-site and analyse numerous well-distributed peat cores per site; ii) statistically test the effect between fire occurrence (i.e. the presence of charcoal macrofossils) and vegetation change throughout the peat profile; and, iii) examine the effect of other explanatory variables (e.g. climate, drainage, grazing) on historical vegetation change within upland peatlands. Ideally, any findings that emerge from paleoecology studies should also be confirmed using experimental approaches.

6.2. Fauna

6.2.1. Birds

P. apricaria prefers shorter areas of vegetation in which to breed (Whittingham et al., 2000; Whittingham et al., 2002). Thus, managed burning could be used to promote *P. apricaria* breeding habitat on upland peatland (Whitehead and Baines, 2018). But the same result could be achieved by mowing. Therefore, one research priority would be to establish whether managed burning or mowing best promotes *P. apricaria* breeding habitat. Such studies should also consider the wider environmental impacts (e.g. on water quality, GHG emissions, flood mitigation) and practicalities of both vegetation management techniques (e.g. getting equipment to inaccessible areas).

Future studies should also: i) use more experimental approaches in order to better establish if any relationships exist between managed burning and the abundance of certain bird species on upland peatlands; ii) determine how managed burning influences bird populations on upland peatland (e.g. by changes to habitat structure, food resources or predation exposure); iii) examine the wider implications of burning induced changes to bird populations within upland peatlands (e.g. the effect on upland peatland food webs); and, iv) attempted to separate the impact of burning from other aspects of grouse moor management, such as predator control.

6.2.2. Aquatic invertebrates

To accurately establish the effect of managed burning on aquatic invertebrate communities within upland peatlands, we need a greater number of high-quality or very high-quality studies (see Table 2 and 3). A priority should be to use study designs that do not confound site with burning management (burning versus no burning) so that the effect of managed burning can be isolated from other environmental or management variables. Once we understand how managed burning influences aquatic invertebrate communities, we can assess the wider implications of any findings that emerge. For example, how burning induced changes influence within stream invertebrate-mediated ecosystem services or peatland food webs.

6.2.3. Soil microorganisms

Only two studies investigated the impact of managed burning on peatland soil microorganisms. Thus, much more research is required to clarify the effect of burning on the different microorganisms living within upland peatland soils. Once this is established, we can examine the wider implications of any research findings that emerge. For example, whether the taxa promoted or inhibited by managed burning promote or inhibit different peatland ecosystem services (e.g. carbon storage and water quality).

6.3. Carbon sequestration and greenhouse gas emissions

6.3.1. Carbon and peat accumulation within upland peatland soil profiles

We need a greater number of high-quality and multi-site studies that measure the impact of managed burning on upland peatland carbon and peat accumulation. Any future studies should attempt to examine carbon and peat accumulation throughout the entire peat profile (i.e. by using full-length cores) using multiple peat cores that are well distributed across each study site or treatment plot. Furthermore, calculations of carbon and peat accumulation should take account of detailed soil bulk density and carbon content assessments (sensu Heinemeyer et al., 2018).

6.3.2. Upland peatland carbon fluxes

The contradictory results across studies suggest that more work is required to establish the relationship between managed burning and upland peatland carbon fluxes. The work of Walker et al. (2016) and Ward et al. (2013) indicates that vegetation composition may be a key driver of upland peatland carbon fluxes. Thus, future work should investigate how changes to upland peatland vegetation composition mediated by managed burning influences ecosystem carbon fluxes. Moreover, none of the carbon flux studies included in this review took measurements across a complete burning rotation – this research gap clearly needs to be addressed.

6.3.3. Upland peatland methane fluxes

The contradictory results across studies suggest that additional research is required to establish the relationship between managed burning and upland peatland methane fluxes. Given that most of the methane flux studies included in this review took measurements for three years or less (i.e. they are short-term assessments), future studies should attempt to capture methane fluxes over at least an entire burning rotation (see Harper et al., 2018). Furthermore, a recent meta-analysis of 87 studies covering 186 sites suggests that peatland methane emissions are primarily driven by water table depth, vegetation composition, pH and temperature (Abdalla et al., 2016). Consequently, future studies should also measure these covariates to see how they interact with burning management to influence upland peatland methane fluxes.

6.3.4. Upland peatland dissolved organic carbon fluxes

The contradictory results suggest that more research is required to fully understand any causal links between burning and DOC fluxes from upland peatlands. Any future studies should try to move away from plot scale measurements and calculate the impact of burning management on DOC fluxes at the catchment scale.

6.3.5. Charcoal production

Given the low number of studies and the debate surrounding the results of Heinemeyer et al. (2018) (Evans et al., 2019; Heinemeyer et al., 2019b), we clearly need more data on the contribution of charcoal to upland peatland carbon budgets. Also, to address some of the criticisms of Heinemeyer et al. (2018) (see Evans et al., 2019; Heinemeyer et al., 2019b) and improve our knowledge of how charcoal influences upland peatland carbon budgets, future studies must: i) include an unburnt control[28]); ii) use a greater number of peat cores spread across a wider area within each study site or plot (Heinemeyer et al., 2018 used three cores per site that were each within a five-metre radius); and, iii) use complete peat core sections to address the criticisms of Young et al. (2019) outlined above (or provide evidence that no deep carbon losses have occurred, e.g. peat profile data on constant or increasing carbon content).

6.3.6. Upland peatland greenhouse gas budgets

We clearly need a greater number of high-quality studies that assess the impact of managed burning on GHG budgets within upland peatlands. Future studies should attempt to measure (rather than estimate or model) each individual pathway that contributes to upland peatland GHG budgets, including the contribution of charcoal (Worrall et al., 2013a; Heinemeyer et al., 2018; Leifeld et al., 2018). Such assessments should also be carried out over the entire burning rotation.

6.4. Water quality and flow

6.4.1. Water quality

We need a much greater number of higher-quality studies that measure burning impacts on water quality directly. This would enable us to accurately detect any causal links that exist between managed burning and different water quality metrics. To achieve this aim, future studies must examine burning impacts on peatland water quality across multiple sites, at the

[28] Heinemeyer et al. (2018) explored relationships between different peat property variables. Therefore, a control was not required and the work by Heinemeyer et al. (2018) should be considered as the first step in exploring a causal relationship between burning frequency, charcoal concentrations in the peat profile and carbon accumulation. The next step would be to carry out a more robust study that would enable causal links to be established.

catchment scale, and, to allow comparisons between studies, use similar methodologies and measure the same water quality metrics. We also need to know the wider ecological and societal implications of any changes to water quality metrics that are mediated by burning management (i.e. does it matter that burning leads to a small decrease in stream water pH?) and whether any potential damage could be mitigated by improving burning practice (burning away from watercourses) or habitat manipulation (e.g. gill planting).

6.4.2. Water flow

We clearly need a much greater number of high-quality studies that measure burning impacts on overland flow and streamflow within upland peatlands. Once we have established robust causal links between managed burning and peatland hydrology, we can investigate the wider implications and whether any potential damage could be mitigated by improving burning practice (burning away from watercourses) or habitat manipulation downstream (e.g. coarse woody debris)?

6.5. Fire ecology

6.5.1. Burn severity

We need many more studies that investigate the effect of burn severity on a wider range of environmental parameters within upland peatlands. Once we have this information, we will be able to manipulate the temperatures of managed burns (by using local environmental conditions – such as peat and vegetation moisture) so that they do not exceed the threshold temperature over which multiple ecosystem services are adversely affected. Finally, to get an accurate and complete picture, future studies should assess the impact of different burn severities across entire burning rotations.

6.5.2. Burn frequency

We desperately need studies that investigate how burning frequency affects a wider range of environmental parameters on upland peatland (rather than just vegetation composition). Such studies should also try to reduce the geographic bias within the evidence base (e.g. all but one study used the Hard Hill experimental plots).

6.6. Wildfire

6.6.1. Fuel loads

WILDFIRE

"Even the latest data on burning extent and frequency is ten years out of date and may have now changed with extensive wildfires, some very severe, having occurred in the last three years."

We clearly need more studies that measure the impact of burning on fuel loads within upland peatlands. These studies should ideally be from a wide range of peatland sites across the British uplands to reduce the current geographical bias within the evidence base (e.g. fuel load studies are predominantly restricted to data collected from the Hard Hill plots). More importantly, we need to know whether reductions in fuel loads mediated by managed burning reduces wildfire risk and damage. For example, an increase in fuel loads on upland peatlands is likely to increase the severity of any wildfires that take hold (Davies et al., 2010b; Davies et al., 2016a). Crucially, high severity wildfires could potentially be extremely damaging to the moss, litter and soil layers within upland peatlands (Davies et al., 2010b; Grau-Andrés et al., 2017; Grau-Andrés et al., 2018; Taylor et al., 2018; Grau-Andrés et al., 2019a; Noble et al., 2019a).

Alternatively, peatland rewetting (e.g. by gulley and ditch blocking), combined with the cessation of vegetation management (e.g. managed burning or cutting) and the planting of *Sphagnum* spp., has been put forward as a better and less damaging way of reducing wildfire risk on upland peatlands (Baird et al., 2019). Proponents of the rewetting hypothesis state that: "*Naturally wet and rewetted peatlands do not experience deep burning because a suite of ecohydrological processes and bog moss traits maintain a surface with a high moisture content, and thereby increase the energy required to ignite peat and restrict the burn depth if fires do occur*" (*ibid*).

It is certainly possible that wetter peatlands *could* reduce the chances of the moss and peat layers igniting or limit the spread of a fire if the moss and peat did ignite. For example, a group of British studies show that the soil and moss layer within (wet) blanket bog ecosystems are generally buffered from the effects of a managed burn, whereas the soil and moss layer within (drier) heathland ecosystems is not (Grau-Andrés et al., 2017; Grau-Andrés et al., 2018; Grau-Andrés et al., 2019a; Grau-Andrés et al., 2019b). But these studies were testing the effect of a management burn (*ibid*). Such burns are carried out in winter during saturated soil conditions, which means they are likely to be significantly cooler than wildfires (especially at the soil surface) (Davies et al., 2010a; Davies et al., 2010b; Davies et al., 2016b). Furthermore, upland peatlands of the UK are largely heather dominated even across areas with more 'natural' (i.e. high) water tables[29] (Lee et al., 2013a; Alday et al., 2015; Milligan et al., 2018; Marrs et al., 2019b). Consequently, rewetted upland peatlands with

[29] The peatland underlying the Hard Hill plots has water tables like that of 'natural' peatland (see Marrs et al., 2019b and references therein). Note also, that summer water tables within 'natural' peatlands can drop to well below (~34 cm) the surface (*ibid*). Thus, the soil surface and moss layers within rewetted peatlands may still be dry, and thereby easily ignitable, during the summer months.

unmanaged vegetation are likely to have high fuel loads, which would lead to higher fire temperatures if a wildfire does manage to ignite (Hobbs and Gimingham, 1984; Davies et al., 2010b; Davies et al., 2016a; Noble et al., 2019a). Furthermore, ignition is certainly possible in summer when bog vegetation becomes very dry, especially during the prolonged dry spells that are becoming more frequent. For example, heather moisture content only has to drop below 60% for it to become flammable (Davies and Legg, 2011). The key question is: would the temperatures during summer wildfires be high enough to ignite the peat within rewetted areas of upland peatland? In truth, we do not know. Thus, the wildfire mitigation potential of rewetting and managed burning both require urgent research attention

6.7. Burning extent

We need more studies at the moorland, regional and national scale that use validated (i.e. ground-truthed) methodologies which include more recent (2015 up to 2020) measurements of burning extent, frequency, return intervals and patch sizes. Once we have accurate estimates of these parameters, we can assess the wider implications of any findings that emerge. However, this will also require a complete understanding of burning impacts, as well as the relationship between burning extent and peatland ecosystem services at the moorland, regional and national scale.

6.8. Soils

6.8.1. Post-fire soil temperatures

Due to the contradictory results reported between studies, more research is required to fully establish the effect of burning on post-fire peatland soil temperatures. Moreover, we have no idea whether small and seasonal differences in mean post-fire soil temperatures are ecologically relevant, that is, do small post-burn increases in mean soil temperatures ($<1^{o}C$) significantly reduce peatland ecosystem functioning.

6.8.2. Soil compaction, moisture and chemistry

Due to the inconsistent results across studies, more research is required to clarify the effect of burning on peatland soil compaction, moisture and chemistry and how these different soil parameters influence the provision of peatland ecosystem services.

6.8.3. Upland peatland soil erosion

More research is required to clarify the effect of burning on peatland soil erosion. Future studies should avoid using erosion pins and instead try to develop more robust methods of measuring peatland soil erosion (perhaps at the catchment scale so that fluvial export of peat can be measured).

6.9. Notes for policymakers, land managers and peatland researchers

Policymakers and land managers require robust and conclusive evidence to underpin decision-making (Sutherland et al., 2004; Pullin and Knight, 2009; Dicks et al., 2014a; Dicks et al., 2014b). However, it would be unwise to use the results of this review to develop clear policy and land management advice because of the considerable uncertainty within the evidence base. Thus, moving forward, peatland researchers must work together to fill research gaps and develop an objective approach for summarising a highly heterogeneous evidence base. Hopefully, the data collated during this review will provide the foundations for achieving the latter objective. Indeed, collating and categorising the complete managed burning evidence base should be an urgent research priority. Another priority moving forward is to develop a series of standardised protocols for measuring managed burning impacts on peatland ecosystem services. This would enable researchers to assess the impact of managed burning using objective approaches, such as meta-analysis.

7. Evidence summary table

Table 9 below summarises the findings of this review and notes whether they are consistent with Glaves et al. (2013). A detailed evidence summary table key is provided in Table 10.

Table 9. Evidence summaries for each of the outcome measure investigated within this review. A description of the data contained in each column is given in Table 10 below.

Sub-question	Outcome measure	Is the evidence consistent?	Direction of evidence	Further info	Evidence profile	Strength of evidence	Consistent with Glaves et al. (2013)?
Flora	Vegetation diversity	No	NA	NA	Positive: 2++, 2+, 1- Negative: 0 Neutral: 1++, 1-	NA	Yes
	Sphagnum diversity	No	NA	NA	Positive: 1- Negative: 0 Neutral: 0	NA	No
	Surface microtopography	No	NA	NA	Positive: 0 Negative: 1++, 1+ Neutral: 1++, 1-	NA	No
	Canopy height	Yes	Negative	This is a short to medium-term impact which is reversed once the vegetation canopy has regrown after ~10-20 years. Thus, frequent burning would have a negative impact on canopy height, but for longer rotations, the impact would be Neutral.	Positive: 0 Negative: 2++, 2+, 2- Neutral: 1+	Very weak	Not assessed by Glaves et al. (2013)

Table 9. Continued.

Sub-question	Outcome measure	Is the evidence consistent?	Direction of evidence	Further info	Evidence profile	Strength of evidence	Consistent with Glaves et al. (2013)?
Flora	*Sphagnum* abundance (principally *Sphagnum capillifolium*)	Yes	Neutral	When considering different rotation lengths or times since burning, burning seems to have a neutral impact on *Sphagnum* abundance relative to non-intervention.	Positive: 0 Negative: 2- Neutral: 3++, 2+, 3-	Weak	No
	Sphagnum capillifolium damage	Yes	Positive	Burning causes temperature-induced damage to *S. capillifolium.* However, two out of the studies suggest that *S. capillifolium* plants recover within under three years.	Positive: 2++, 1+ Negative: 0 Neutral: 0	Very weak	Not assessed by Glaves et al. (2013)
	Sphagnum propagules in surface peat	No	NA	NA	Positive: 0 Negative: 1+ Neutral: 0	NA	Not assessed by Glaves et al. (2013)
	*Eriophorum a*bundance	No	NA	NA	Positive: 3++, 1- Negative: 1++, 1- Neutral: 1++, 2+, 2-	NA	No
	Calluna vulgaris abundance	Yes	Negative	This is a short-term impact. Heather becomes more abundant and eventually dominant with increasing time since burn. Thus, *C. vulgaris* abundance is lowest on recently and/or frequently burnt areas, and highest on unmanaged areas.	Positive: 1- Negative: 6++, 4+, 3- Neutral: 0	Moderate	Yes
	*Calluna vulgaris g*ermination	No	NA	NA	Positive: 1++ Negative: 0 Neutral: 0	NA	Not assessed by Glaves et al. (2013)

Table 9. Continued.

Sub-question	Outcome measure	Is the evidence consistent?	Direction of evidence	Further info	Evidence profile	Strength of evidence	Consistent with Glaves et al. (2013)?
Flora	*Calluna vulgaris* propagules in litter and surface peat	No	NA	NA	Positive: 0 Negative: 1+ Neutral: 0	NA	Not assessed by Glaves et al. (2013)
	Amount of bare ground	Yes	Positive	Burning leads to the small-scale increase in bare ground, but this seems to be a transient effect (lasting four to ten years).	Positive: 1++, 3+, 1- Negative: 0 Neutral: 1-	Very weak	Yes
	Sphagnum historical abundance	Yes	Negative	Circumstantial evidence from peat cores suggests that episodes of fire (denoted by charcoal macrofossils) are coincident with a decline in *Sphagnum* macrofossils.	Positive: 0 Negative: 1+, 7- Neutral: 1-	Very weak	Not assessed by Glaves et al. (2013)
	Eriophorum historical abundance	No	NA	NA	Positive: 1+, 3- Negative: 1- Neutral: 1-	NA	Not assessed by Glaves et al. (2013)
	Calluna vulgaris historical abundance	No	NA	NA	Positive: 5- Negative: 1- Neutral: 2+, 1-	NA	Not assessed by Glaves et al. (2013)

Table 9. Continued.

Sub-question	Outcome measure	Is the evidence consistent?	Direction of evidence	Further info	Evidence profile	Strength of evidence	Consistent with Glaves et al. (2013)?
Fauna	*Pluvialis apricaria* populations	Yes	Positive	Note: managed burning often coincides with predator control, which means it is hard to determine the relative contribution of managed burning in promoting *P. apricaria* populations	Positive: 6+ Negative: 0 Neutral: 0	Very weak	Yes
	Cranefly emergence	No	NA	NA	Positive: 0 Negative: 0 Neutral: 1++	NA	Not assessed by Glaves et al. (2013)
	Aquatic invertebrate diversity	No	NA	NA	Positive: 0 Negative: 2- Neutral: 1-	NA	No
	Abundance of pollution tolerant aquatic invertebrates	No	NA	NA	Positive: 2- Negative: 0 Neutral: 1-	NA	No
	Abundance of pollution intolerant aquatic invertebrates	No	NA	NA	Positive: 0 Negative: 2- Neutral: 1-	NA	No
	Soil microorganisms	No	NA	NA	Studies: 1++, 1-	NA	Not assessed by Glaves et al. (2013)

Table 9. Continued.

Sub-question	Outcome measure	Is the evidence consistent?	Direction of evidence	Further info	Evidence profile	Strength of evidence	Consistent with Glaves et al. (2013)?
Carbon sequestration and GHG emissions	Carbon accumulation	Yes	Neutral	Both studies suggest that burnt areas of blanket bog accumulate (rather than lose) carbon within the peat profile. One study suggests that carbon accumulation rates on blanket bog subject to longer burning rotations (~20 years) appear broadly the same as those recorded in unburnt or not recently burnt areas.	Positive: 0 Negative: 0 Neutral: 1++, 1+	Very weak	No
	Peat accumulation	No	NA	NA	Positive: 0 Negative: 0 Neutral: 1++	NA	No
	Carbon fluxes	No	NA	NA	Positive: 1++, 1+ Negative: 1+ Neutral: 4++, 1-	NA	No
	Methane fluxes	No	NA	NA	Positive: 1++, 1+ Negative: 0 Neutral: 3++	NA	Not assessed by Glaves et al. (2013)
	Dissolved organic carbon fluxes	Yes	Neutral	NA	Positive: 1++ Negative: 0 Neutral: 1++, 2+, 1-	Low	No
	Influence of charcoal on carbon storage	Yes	Positive	The production of charcoal during managed burning and its subsequent incorporation into the peat profile may have positive impacts on long-term carbon storage.	Positive: 1+, 1- Negative: 0 Neutral: 0	Very weak	Not assessed by Glaves et al. (2013)

Table 9. Continued.

Sub-question	Outcome measure	Is the evidence consistent?	Direction of evidence	Further info	Evidence profile	Strength of evidence	Consistent with Glaves et al. (2013)?
Carbon sequestration and GHG emissions	Greenhouse gas budgets	No	NA	Note: in relation to the direction of evidence, "Positive" means increased GHG emissions and "Negative" means reduced GHG emissions relative to unburnt or not recently burnt controls.	Positive: 1++ Negative: 1- Neutral: 0	NA	Yes
Water quality and flow	Water colour	Yes	Neutral	Note: two of the three studies measured water colour at the plot scale (in soil pore water or overland flow), whereas the third study measured water colour at the catchment scale (within stream water).	Positive: 0 Negative: 0 Neutral: 1++, 1+, 1-	Very weak	No
	pH	No	NA	NA	Positive: 0 Negative: 1- Neutral: 1++, 1-	NA	No
	Water table depth	No	NA	Note: in relation to the direction of evidence, "Positive" means higher water tables and "Negative" means lower water tables relative to unburnt or not recently burnt controls.	Positive: 1- Negative: 1++, 1- Neutral: 0	NA	No
	Overland flow	Yes	Positive	NA	Positive: 2- Negative: 0 Neutral: 0	Very weak	Yes
	Streamflow	No	NA	NA	Positive: 1- Negative: 0 Neutral: 1-	NA	Not assessed by Glaves et al. (2013)

Table 9. Continued.

Sub-question	Outcome measure	Is the evidence consistent?	Direction of evidence	Further info	Evidence profile	Strength of evidence	Consistent with Glaves et al. (2013)?
Fire ecology	Fire severity and *Sphagnum capillifolium* damage	Yes	Positive	There was a positive relationship between burn severity and *S. capillifolium* damage, with lower burn severities causing minimal damage to *S. capillifolium* plants relative to unburnt controls. Nevertheless, *S. capillifolium* plants are still able to recover after experiencing high severity burns.	Positive: 2++, 1+ Negative: 0 Neutral: 0	Very weak	Not assessed by Glaves et al. (2013)
	Burn frequency and *Calluna vulgaris* abundance	Yes	Negative	Note: the evidence is exclusively from the Hard Hill experimental plots.	Positive: 0 Negative: 3+, 1+ Neutral: 0	Very weak	No
	Burn frequency and *Eriophorum* abundance	Yes	Positive	Note: the evidence is exclusively from the Hard Hill experimental plots.	Positive: 2++ Negative: 0 Neutral: 0	Very weak	No
	Burn frequency and *Sphagnum* abundance (mainly *S. capillifolium*)	Yes	Neutral	Note: the evidence is exclusively from the Hard Hill experimental plots.	Positive: 0 Negative: 0 Neutral: 3++	Weak	Not assessed by Glaves et al. (2013)
	Carbon accumulation	NA	NA	NA	Positive: 1+ Negative: 1++ Neutral: 0	NA	Not assessed by Glaves et al. (2013)
	Peat accumulation	NA	NA	NA	Positive: 0 Negative: 1++ Neutral: 0	NA	Not assessed by Glaves et al. (2013)

Table 9. Continued.

Sub-question	Outcome measure	Is the evidence consistent?	Direction of evidence	Further info	Evidence profile	Strength of evidence	Consistent with Glaves et al. (2013)?
Wildfire	Fuel loads	Yes	Negative	NA	Positive: 0 Negative: 3++ Neutral: 0	Weak	Yes
Burning extent and frequency	Current extent	NA	NA	NA	Studies: 3+	NA	No
	Temporal changes in extent	Yes	Positive	Note: one study was from a single moorland site, and the second study did not validate the method used to calculate burning extent and only assessed 2% of the English uplands. Moreover, both studies are out of date because their last sampling point was over ten years ago – burning extent may have changed since then.	Positive: 2+ Negative: 0 Neutral: 0	Very weak	No
	Burn return intervals	No	NA	NA	Studies: 2+	NA	No
	Temporal changes in frequency	Yes	Positive	Note: one study was from a single moorland site, and the second study did not validate the method used to calculate burning extent and only assessed 2% of the English uplands. Moreover, both studies are out of date because their last sampling point was over ten years ago – the trend in burning frequency may have changed since then. Also, in one study, burning frequencies were highly variable between years.	Positive: 2+ Negative: 0 Neutral: 0	Very weak	No

Table 9. Continued.

Sub-question	Outcome measure	Is the evidence consistent?	Direction of evidence	Further info	Evidence profile	Strength of evidence	Consistent with Glaves et al. (2013)?
Burning extent and frequency	Burn patch size	No	NA	NA	Studies: 1+	NA	Not assessed by Glaves et al. (2013)
Soils	Post-fire soil temperatures	Yes	Neutral	NA	Positive: 1- Negative: 0 Neutral: 1++, 2+	Weak	Not assessed by Glaves et al. (2013)
	Soil compaction	No	NA	NA	Positive: 2++ Negative: 0 Neutral: 1+, 1-	NA	No
	Soil moisture	No	NA	NA	Positive: 0 Negative: 2++ Neutral: 1+	NA	Not assessed by Glaves et al. (2013)
	Soil chemistry (various metrics)	No	NA	NA	Studies: 2-	NA	No
	Soil erosion	No	NA	NA	Positive: 1- Negative: 0 Neutral: 0	NA	No

Table 10. A descriptive key to the evidence summary table (Table 9)

Sub-question	The review sub-question to which the evidence applies.
Outcome measure	The outcome measure being assessed.
Is the evidence consistent?	Evidence was only classified as consistent if ≥75% of the studies for a given outcome variable reported similar results (positive, negative, or neutral).
Direction of evidence	If the evidence is consistent, does it indicate burning has a positive, negative, or neutral impact on the selected outcome variable? Note that "positive" and "negative" are not value judgements (i.e. better or worse) – *they relate to the direction of evidence*.
Further info	Clarificatory information about the evidence for the selected outcome measure.
Evidence profile	The number and quality of studies reporting a positive, negative, or neutral effect of managed burning. Note that "positive" and "negative" are not value judgements (i.e. better or worse) – *they relate to the direction of evidence*.
Strength of evidence	Strong, Moderate, Weak or Very weak.
Consistent with Glaves et al. (2013)?	Are the findings for the selected outcome variable consistent with the findings of Glaves et al. (2013)? Yes, No or Not assessed by Glaves et al. (2013).

References

ABDALLA, M., HASTINGS, A., TRUU, J., ESPENBERG, M., MANDER, Ü. & SMITH, P. 2016. Emissions of methane from northern peatlands: a review of management impacts and implications for future management options. *Ecology and Evolution,* 6**,** 7080-7102.

ALBERTSON, K., AYLEN, J., CAVAN, G. & MCMORROW, J. 2009. Forecasting the outbreak of moorland wildfires in the English Peak District. *Journal of Environmental Management,* 90**,** 2642-2651.

ALBERTSON, K., AYLEN, J., CAVAN, G. & MCMORROW, J. 2010. Climate change and the future occurrence of moorland wildfires in the Peak District of the UK. *Climate Research,* 45**,** 105-118.

ALDAY, J. G., SANTANA, V. M., LEE, H., ALLEN, K. A. & MARRS, R. H. 2015. Above-ground biomass accumulation patterns in moorlands after prescribed burning and low-intensity grazing. *Perspectives in Plant Ecology, Evolution and Systematics,* 17**,** 388-396.

ALLEN, K. A., DENELLE, P., RUIZ, F. M. S., SANTANA, V. M. & MARRS, R. H. 2016. Prescribed moorland burning meets good practice guidelines: A monitoring case study using aerial photography in the Peak District, UK. *Ecological Indicators,* 62**,** 76-85.

ALLEN, S. 1964. Chemical aspects of heather burning. *Journal of Applied Ecology***,** 347-367.

ASHBY, M. A. & HEINEMEYER, A. 2019a. Prescribed burning impacts on ecosystem services in the British uplands: A methodological critique of the EMBER project. *Journal of Applied Ecology,* 00**,** 1-9.

ASHBY, M. A. & HEINEMEYER, A. 2019b. 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). *EcoEvoRxiv,* October 31.

AXMANOVÁ, I., TICHÝ, L., FAJMONOVÁ, Z., HÁJKOVÁ, P., HETTENBERGEROVÁ, E., LI, C.-F., MERUNKOVÁ, K., NEJEZCHLEBOVÁ, M., OTÝPKOVÁ, Z., VYMAZALOVÁ, M. & ZELENÝ, D. 2012. Estimation of herbaceous biomass from species composition and cover. *Applied Vegetation Science,* 15**,** 580-589.

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., THOM, T., WADDINGTON, J. M. & YOUNG, D. M. 2019. Validity of managing peatlands with fire. *Nature Geoscience,* 12**,** 884-885.

BENSCOTER, B. W. & VITT, D. H. 2008. Spatial Patterns and Temporal Trajectories of the Bog Ground Layer Along a Post-Fire Chronosequence. *Ecosystems,* 11**,** 1054-1064.

BLUNDELL, A. & HOLDEN, J. 2015. Using palaeoecology to support blanket peatland management. *Ecological Indicators,* 49**,** 110-120.

BRAMER, W. M., GIUSTINI, D., DE JONGE, G. B., HOLLAND, L. & BEKHUIS, T. 2016. De-duplication of database search results for systematic reviews in EndNote. *Journal of the Medical Library Association : JMLA,* 104**,** 240-243.

BROWN, L. E. & HOLDEN, J. 2019. Contextualising UK moorland burning studies: geographical versus potential sponsorship-bias effects on research conclusions. *bioRxiv***,** 731117.

BROWN, L. E., HOLDEN, J. & PALMER, S. M. 2016. Moorland vegetation burning debates should avoid contextomy and anachronism: a comment on Davies et al.(2016). *Philosophical Transactions of the Royal Society B: Biological Sciences,* 371**,** 20160432.

BROWN, L. E., HOLDEN, J., PALMER, S. M., JOHNSTON, K., RAMCHUNDER, S. J. & GRAYSON, R. 2015a. Effects of fire on the hydrology, biogeochemistry, and ecology of peatland river systems. *Freshwater Science,* 34**,** 1406-1425.

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.

BROWN, L. E., PALMER, S. M., JOHNSTON, K. & HOLDEN, J. 2015b. Vegetation management with fire modifies peatland soil thermal regime. *Journal of environmental management,* 154**,** 166-176.

BUCHANAN, G. M., PEARCE-HIGGINS, J. W., DOUGLAS, D. J. T. & GRANT, M. C. 2017. Quantifying the importance of multi-scale management and environmental variables on moorland bird abundance. *Ibis,* 159**,** 744-756.

CALLADINE, J., CRITCHLEY, C. N. R., BAKER, D., TOWERS, J. & THIEL, A. 2014. Conservation management of moorland: a case study of the effectiveness of a combined suite of management prescriptions which aim to enhance breeding bird populations. *Bird study,* 61**,** 56-72.

CAMERON, K. H. & LEATHER, S. R. 2012. Heathland management effects on carabid beetle communities: the relationship between bare ground patch size and carabid biodiversity. *Journal of Insect Conservation,* 16**,** 523-535.

CHAMBERS, F. M., CLOUTMAN, E., DANIELL, J., MAUQUOY, D. & JONES, P. 2013. Long-term ecological study (palaeoecology) to chronicle habitat degradation and inform conservation ecology: an exemplar from the Brecon Beacons, South Wales. *Biodiversity and Conservation,* 22**,** 719-736.

CHAMBERS, F. M., CROWLE, A., DANIELL, J. R., MAUQUOY, D., MCCARROLL, J., SANDERSON, N., THOM, T., TOMS, P. & WEBB, J. C. 2017. Ascertaining the nature and timing of mire degradation: using palaeoecology to assist future conservation management in Northern England. *AIMS Environmental Science,* 4**,** 54-82.

CLAY, G. D., WORRALL, F. & AEBISCHER, N. J. 2015. Carbon stocks and carbon fluxes from a 10-year prescribed burning chronosequence on a UK blanket peat. *Soil use and management,* 31**,** 39-51.

CLYMO, R. S. & DUCKETT, J. G. 1986. Regeneration of Sphagnum. *New Phytologist,* 102**,** 589-614.

DALLIMER, M., SKINNER, A. M., DAVIES, Z. G., ARMSWORTH, P. R. & GASTON, K. J. 2012. Multiple habitat associations: the role of offsite habitat in determining onsite avian density and species richness. *Ecography,* 35**,** 134-145.

DAVIES, G. M., DOMÈNECH, R., GRAY, A. & JOHNSON, P. C. D. 2016a. Vegetation structure and fire weather influence variation in burn severity and fuel consumption during peatland wildfires. *Biogeosciences,* 13**,** 389-398.

DAVIES, G. M. & GRAY, A. 2015. Don't let spurious accusations of pseudoreplication limit our ability to learn from natural experiments (and other messy kinds of ecological monitoring). *Ecology and Evolution,* 5**,** 5295-5304.

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. 2016b. The role of fire in UK peatland and moorland management: the need for informed, unbiased debate. *Phil. Trans. R. Soc. B,* 371**,** 20150342.

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. 2016c. The peatland vegetation burning debate: keep scientific critique in perspective. A response to Brown et al. and Douglas et al. *Philosophical Transactions of the Royal Society B: Biological Sciences,* 371**,** 20160434.

DAVIES, G. M. & LEGG, C. J. 2011. Fuel Moisture Thresholds in the Flammability of Calluna vulgaris. *Fire Technology,* 47**,** 421-436.

DAVIES, G. M., LEGG, C. J., O'HARA, R., MACDONALD, A. J. & SMITH, A. A. 2010a. Winter desiccation and rapid changes in the live fuel moisture content of Calluna vulgaris. *Plant Ecology & Diversity,* 3**,** 289-299.

DAVIES, G. M., SMITH, A. A., MACDONALD, A. J., BAKKER, J. D. & LEGG, C. J. 2010b. Fire intensity, fire severity and ecosystem response in heathlands: factors affecting the regeneration of Calluna vulgaris. *Journal of Applied Ecology,* 47**,** 356-365.

DAVIES, G. M., STOOF, C. R., KETTRIDGE, N. & GRAY, A. 2016d. Comment on: Vegetation burning for game management in the UK uplands is increasing and overlaps spatially with soil carbon and protected areas. *Biological Conservation,* 195**,** 293-294.

DICKS, L. V., HODGE, I., RANDALL, N. P., SCHARLEMANN, J. P., SIRIWARDENA, G. M., SMITH, H. G., SMITH, R. K. & SUTHERLAND, W. J. 2014a. A transparent process for "evidence-informed" policy making. *Conservation Letters,* 7**,** 119-125.

DICKS, L. V., WALSH, J. C. & SUTHERLAND, W. J. 2014b. Organising evidence for environmental management decisions: a '4S'hierarchy. *Trends in ecology & evolution,* 29**,** 607-613.

DIXON, S. D., WORRALL, F., ROWSON, J. G. & EVANS, M. G. 2015. Calluna vulgaris canopy height and blanket peat CO2 flux: Implications for management. *Ecological Engineering,* 75**,** 497-505.

DOUGLAS, D. J., BELLAMY, P. E., STEPHEN, L. S., PEARCE–HIGGINS, J. W., WILSON, J. D. & GRANT, M. C. 2014. Upland land use predicts population decline in a globally near-threatened wader. *Journal of applied ecology,* 51**,** 194-203.

DOUGLAS, D. J., BERESFORD, A., SELVIDGE, J., GARNETT, S., BUCHANAN, G. M., GULLETT, P. & GRANT, M. C. 2017. Changes in upland bird abundances show associations with moorland management. *Bird Study,* 64**,** 242-254.

DOUGLAS, D. J., BUCHANAN, G. M., THOMPSON, P., AMAR, A., FIELDING, D. A., REDPATH, S. M. & WILSON, J. D. 2015. Vegetation burning for game management in the UK uplands is increasing and overlaps spatially with soil carbon and protected areas. *Biological Conservation,* 191**,** 243-250.

DOUGLAS, D. J., BUCHANAN, G. M., THOMPSON, P. & WILSON, J. D. 2016a. The role of fire in UK upland management: the need for informed challenge to conventional wisdoms: a comment on Davies et al.(2016). *Philosophical Transactions of the Royal Society B: Biological Sciences,* 371**,** 20160433.

DOUGLAS, D. J. T., BUCHANAN, G. M., THOMPSON, P., SMITH, T., COLE, T., AMAR, A., FIELDING, D. A., REDPATH, S. M. & WILSON, J. D. 2016b. Reply to comment on: Vegetation burning for game management in the UK uplands is increasing and overlaps spatially with soil carbon and protected areas. *Biological Conservation,* 195**,** 295-296.

DOUGLAS, D. J. T. & PEARCE-HIGGINS, J. W. 2014. Relative importance of prey abundance and habitat structure as drivers of shorebird breeding success and abundance. *Animal Conservation,* 17**,** 535-543.

ELLIOTT, J. H., SYNNOT, A., TURNER, T., SIMMONDS, M., AKL, E. A., MCDONALD, S., SALANTI, G., MEERPOHL, J., MACLEHOSE, H., HILTON, J., TOVEY, D., SHEMILT, I., THOMAS, J., AGORITSAS, T., HILTON, J., PERRON, C., AKL, E., HODDER, R., PESTRIDGE, C., ALBRECHT, L., HORSLEY, T., PLATT, J., ARMSTRONG, R., NGUYEN, P. H., PLOVNICK, R., ARNO, A., IVERS, N., QUINN, G., AU, A., JOHNSTON, R., RADA, G., BAGG, M., JONES, A., RAVAUD, P., BODEN, C., KAHALE, L., RICHTER, B., BOISVERT, I., KESHAVARZ, H., RYAN, R., BRANDT, L., KOLAKOWSKY-HAYNER, S. A., SALAMA, D., BRAZINOVA, A., NAGRAJ, S. K., SALANTI, G., BUCHBINDER, R., LASSERSON, T., SANTAGUIDA, L., CHAMPION, C., LAWRENCE, R., SANTESSO, N., CHANDLER, J., LES, Z., SCHÜNEMANN, H. J., CHARIDIMOU, A., LEUCHT, S., SHEMILT, I., CHOU, R., LOW, N., SHERIFALI, D., CHURCHILL, R., MAAS, A., SIEMIENIUK, R., CNOSSEN, M. C., MACLEHOSE, H., SIMMONDS, M., COSSI, M.-J., MACLEOD, M., SKOETZ, N., COUNOTTE, M., MARSHALL, I., SOARES-WEISER, K., CRAIGIE, S., MARSHALL, R., SRIKANTH, V., DAHM, P., MARTIN, N., SULLIVAN, K., DANILKEWICH, A., MARTÍNEZ GARCÍA, L., SYNNOT, A., DANKO, K., MAVERGAMES, C., TAYLOR, M., DONOGHUE, E., MAXWELL, L. J., THAYER, K., DRESSLER, C., MCAULEY, J., THOMAS, J., EGAN, C., MCDONALD, S., TRITTON, R., ELLIOTT, J., MCKENZIE, J., TSAFNAT, G., ELLIOTT, S. A., MEERPOHL, J., TUGWELL, P., et al. 2017. Living systematic review: 1. Introduction—the why, what, when, and how. *Journal of Clinical Epidemiology,* 91**,** 23-30.

EUROPEAN COMMISSION. 2017. *April infringements package: key decisions* [Online]. Brussels: European Commission. Available: http://europa.eu/rapid/press-release_MEMO-17-1045_EN.htm [Accessed 20/11/2018].

EVANS, C., ARTZ, R., MOXLEY, J., SMYTH, M.-A., TAYLOR, E., ARCHER, N., BURDEN, A., WILLIAMSON, J., DONNELLY, D., THOMSON, A., BUYS, G., MALCOLM, H., WILSON, D., RENOU-WILSON, F. &

J., P. 2017. Implementation of an emission inventory for UK peatlands. Report to the Department for Business, Energy and Industrial Strategy. Bangor, UK.
EVANS, C. D., BAIRD, A. J., GREEN, S. M., PAGE, S. E., PEACOCK, M., REED, M. S., ROSE, N. L., STONEMAN, R., THOM, T. J., YOUNG, D. M. & GARNETT, M. H. 2019. 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 A. Heinemeyer, Q. Asena, W. L. Burn and A. L. Jones (Geo: Geography and Environment 2018; e00063). *Geo: Geography and Environment,* 6**,** e00075.
FLANAGAN, N. E., WANG, H., WINTON, S. & RICHARDSON, C. J. 2020. Low-severity fire as a mechanism of organic matter protection in global peatlands: Thermal alteration slows decomposition. *Global Change Biology,* n/a.
FYFE, R. M., OMBASHI, H., DAVIES, H. J. & HEAD, K. 2018. Quantified moorland vegetation and assessment of the role of burning over the past five millennia. *Journal of Vegetation Science,* 29**,** 393-403.
FYFE, R. M. & WOODBRIDGE, J. 2012. Differences in time and space in vegetation patterning: analysis of pollen data from Dartmoor, UK. *Landscape ecology,* 27**,** 745-760.
GARNETT, M., INESON, P. & STEVENSON, A. 2000. Effects of burning and grazing on carbon sequestration in a Pennine blanket bog, UK. *The Holocene,* 10**,** 729-736.
GILLINGHAM, P., STEWART, J. & BINNEY, H. 2016. *The historic peat record: Implications for the restoration of blanket bog*, Natural England Evidence Review, Number 011.
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,* Peterborough, UK, Natural England evidence review NEER004.
GRANT, M. J. & BOOTH, A. 2009. A typology of reviews: an analysis of 14 review types and associated methodologies. *Health Information & Libraries Journal,* 26**,** 91-108.
GRAU-ANDRÉS, R., DAVIES, G. M., GRAY, A., SCOTT, E. M. & WALDRON, S. 2018. Fire severity is more sensitive to low fuel moisture content on Calluna heathlands than on peat bogs. *Science of the Total Environment,* 616**,** 1261-1269.
GRAU-ANDRÉS, R., DAVIES, G. M., WALDRON, S., SCOTT, E. M. & GRAY, A. 2019a. Increased fire severity alters initial vegetation regeneration across Calluna-dominated ecosystems. *Journal of Environmental Management,* 231**,** 1004-1011.
GRAU-ANDRÉS, R., GRAY, A. & DAVIES, G. M. 2017. Sphagnum abundance and photosynthetic capacity show rapid short-term recovery following managed burning. *Plant Ecology & Diversity,* 10**,** 353-359.
GRAU-ANDRÉS, R., GRAY, A., DAVIES, G. M., SCOTT, E. M. & WALDRON, S. 2019b. Burning increases post-fire carbon emissions in a heathland and a raised bog, but experimental manipulation of fire severity has no effect. *Journal of Environmental Management,* 233**,** 321-328.
GUNNARSSON, U., MALMER, N. & RYDIN, H. 2002. Dynamics or constancy in Sphagnum dominated mire ecosystems? A 40-year study. *Ecography,* 25**,** 685-704.
HAIDICH, A. B. 2010. Meta-analysis in medical research. *Hippokratia,* 14**,** 29-37.
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.
HEINEMEYER, A., ASENA, Q., BURN, W. L. & JONES, A. L. 2018. Peatland carbon stocks and burn history: Blanket bog peat core evidence highlights charcoal impacts on peat physical properties and long-term carbon storage. *Geo: Geography and Environment,* 5**,** e00063.
HEINEMEYER, A., BERRY, R. & SLOAN, T. J. 2019a. Assessing soil compaction and micro-topography impacts of alternative heather cutting as compared to burning as part of grouse moor management on blanket bog. *PeerJ,* 7**,** e7298.
HEINEMEYER, A., BURN, W. L., ASENA, Q., JONES, A. L. & ASHBY, M. A. 2019b. 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: Geography and Environment,* 6**,** e00078.
HEINEMEYER, A. & VALLACK, H. W. 2015. *Literature review on: potential techniques to address heather dominance and help support 'active' Sphagnum supporting peatland vegetation on blanket peatlands and identify practical management options for experimental testing,* York, UK, University of York draft report to Defra and Natural England.
HEINEMEYER, A., VALLACK, H. W., MORTON, P. A., PATEMAN, R., DYTHAM, C., INESON, P., MCCLEAN, C., BRISTOW, C. & PEARCE-HIGGINS, J. W. 2019c. *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 (Appendix by Richard Lindsay). Final Report to Defra on Project BD5104* York, UK, Stockholm Environment Institute at the University of York.
HOBBS, R. J. & GIMINGHAM, C. H. 1984. Studies on Fire in Scottish Heathland Communities: I. Fire Characteristics. *Journal of Ecology,* 72**,** 223-240.
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.
HURLBERT, S. H. 1984. Pseudoreplication and the Design of Ecological Field Experiments. *Ecological Monographs,* 54**,** 187-211.
JNCC 2009. *Common Standards Monitoring Guidance for Upland Habitats,* Peterborough, UK, Joint Nature Conservation Committee.
JNCC 2011. Towards an assessment of the state of UK peatlands. JNCC Report, 445. . Peterborough, UK: Joint Nature Conservation Committee.
JOHNSTON, K. 2012. Catchment management influences on moorland stream biodiversity. Moors for the future report: MRF610. Edale, UK: Moors for the Future.
JOHNSTON, K. & ROBSON, B. 2015. Experimental effects of ash deposition on macroinvertebrate assemblages in peatland streams. *Marine and Freshwater Research,* 69**,** 1681-1691.
JONES, M. W., SANTÍN, C., VAN DER WERF, G. R. & DOERR, S. H. 2019. Global fire emissions buffered by the production of pyrogenic carbon. *Nature Geoscience,* 12**,** 742-747.
LEE, H., ALDAY, J. G., ROSE, R. J., O'REILLY, J. & MARRS, R. H. 2013a. Long-term effects of rotational prescribed burning and low-intensity sheep grazing on blanket-bog plant communities. *Journal of Applied Ecology,* 50**,** 625-635.
LEE, H., ALDAY, J. G., ROSENBURGH, A., HARRIS, M., MCALLISTER, H. & MARRS, R. H. 2013b. Change in propagule banks during prescribed burning: a tale of two contrasting moorlands. *Biological conservation,* 165**,** 187-197.
LEIFELD, J., ALEWELL, C., BADER, C., KRÜGER, J. P., MUELLER, C. W., SOMMER, M., STEFFENS, M. & SZIDAT, S. 2018. Pyrogenic carbon contributes substantially to carbon storage in intact and degraded Northern peatlands. *Land degradation & development,* 29**,** 2082-2091.
LITTLEWOOD, N. A., MASON, T. H. E., HUGHES, M., JAQUES, R., WHITTINGHAM, M. J. & WILLIS, S. G. 2019. The influence of different aspects of grouse moorland management on nontarget bird assemblages. *Ecology and Evolution,* 9**,** 11089-11101.
LUDWIG, S. C., AEBISCHER, N. J., BUBB, D., RICHARDSON, M., ROOS, S., WILSON, J. D. & BAINES, D. 2018. Population responses of Red Grouse Lagopus lagopus scotica to expansion of heather Calluna vulgaris cover on a Scottish grouse moor. *Avian Conservation and Ecology,* 13.
LUDWIG, S. C., ROOS, S., BUBB, D. & BAINES, D. 2017. Long-term trends in abundance and breeding success of red grouse and hen harriers in relation to changing management of a Scottish grouse moor. *Wildlife Biology,* 2017.
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., SANTANA, V., LEE, H., HALSALL, K. & CHIVERRELL, R. C. 2019a. Experimental evidence for sustained carbon sequestration in fire-managed, peat moorlands. *Nature Geoscience,* 12**,** 108-112.

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., SANTANA, V., LEE, H., HALSALL, K. & CHIVERRELL, R. C. 2019b. Reply to: Validity of managing peatlands with fire. *Nature Geoscience,* 12**,** 886-888.

MARRS, R. H., RAWES, M., ROBINSON, J. S. & POPPITT, S. D. 1986. *Long-term studies of vegetation change at moor house NNR: Guide to recording methods and the database,* Grange-over-Sands, UK, Institute of Terrestrial Ecology.

MCCARROLL, J., CHAMBERS, F. M., WEBB, J. C. & THOM, T. 2016a. Informing innovative peatland conservation in light of palaeoecological evidence for the demise of Sphagnum imbricatum: the case of Oxenhope Moor, Yorkshire, UK. *Mires and Peat,* 18**,** 1-24.

MCCARROLL, J., CHAMBERS, F. M., WEBB, J. C. & THOM, T. 2016b. Using palaeoecology to advise peatland conservation: An example from West Arkengarthdale, Yorkshire, UK. *Journal for Nature Conservation,* 30**,** 90-102.

MCCARROLL, J., CHAMBERS, F. M., WEBB, J. C. & THOM, T. 2017. Application of palaeoecology for peatland conservation at Mossdale Moor, UK. *Quaternary International,* 432**,** 39-47.

MILLIGAN, G., ROSE, R. J., O'REILLY, J. & MARRS, R. H. 2018. Effects of rotational prescribed burning and sheep grazing on moorland plant communities: Results from a 60-year intervention experiment. *Land Degradation & Development,* 29**,** 1397-1412.

MORTON, P. A. & HEINEMEYER, A. 2019. Bog breathing: the extent of peat shrinkage and expansion on blanket bogs in relation to water table, heather management and dominant vegetation and its implications for carbon stock assessments. *Wetlands Ecology and Management,* 27**,** 467-482.

MUUKKONEN, P., MÄKIPÄÄ, R., LAIHO, R., MINKKINEN, K., VASANDER, H. & FINÉR, L. 2006. Relationship between biomass and percentage cover in understorey vegetation of boreal coniferous forests.

NATURAL ENGLAND 2019a. Burning as a tool for the restoration of upland blanket bog: Position Statement from Natural England (UPS01). Peterborough, UK: Natural England.

NATURAL ENGLAND 2019b. Burning as a tool for the restoration of upland blanket bog: Position Statement from Natural England (UPS01), Annex 1 – Position Statement: Interventions for restoration of upland blanket bog. Peterborough, UK: Natural England.

NATURAL ENGLAND 2019c. Burning as a tool for the restoration of upland blanket bog: Position Statement from Natural England (UPS01), Annex 2 – Natural England Upland Habitat Advice Protocol for Upland Peatland Monitoring. Peterborough, UK: Natural England.

NATURAL ENGLAND 2019d. Uplands Burning Position Statement Q&A (v2). Peterborough, UK: Natural England.

NEWEY, S., MUSTIN, K., BRYCE, R., FIELDING, D., REDPATH, S., BUNNEFELD, N., DANIEL, B. & IRVINE, R. J. 2016. Impact of management on avian communities in the Scottish Highlands. *PloS one,* 11**,** e0155473.

NOBLE, A., CROWLE, A., GLAVES, D. J., PALMER, S. M. & HOLDEN, J. 2019a. Fire temperatures and Sphagnum damage during prescribed burning on peatlands. *Ecological Indicators,* 103**,** 471-478.

NOBLE, A., O'REILLY, J., GLAVES, D. J., CROWLE, A., PALMER, S. M. & HOLDEN, J. 2018a. Impacts of prescribed burning on Sphagnum mosses in a long-term peatland field experiment. *PLOS ONE,* 13**,** e0206320.

NOBLE, A., PALMER, S. M., GLAVES, D. J., CROWLE, A., BROWN, L. E. & HOLDEN, J. 2018b. Prescribed burning, atmospheric pollution and grazing effects on peatland vegetation composition. *Journal of Applied Ecology,* 55**,** 559-569.

NOBLE, A., PALMER, S. M., GLAVES, D. J., CROWLE, A. & HOLDEN, J. 2017. Impacts of peat bulk density, ash deposition and rainwater chemistry on establishment of peatland mosses. *Plant and Soil,* 419**,** 41-52.

NOBLE, A., PALMER, S. M., GLAVES, D. J., CROWLE, A. & HOLDEN, J. 2019b. Peatland vegetation change and establishment of re-introduced Sphagnum moss after prescribed burning. *Biodiversity and Conservation*.

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.

PULLIN, A. S. & KNIGHT, T. M. 2009. Doing more good than harm–Building an evidence-base for conservation and environmental management. *Biological conservation,* 142**,** 931-934.

RAWES, M. & HOBBS, R. 1979. Management of semi-natural blanket bog in the northern Pennines. *The Journal of Ecology,* 67**,** 789-807.

ROBERTSON, G. S., NEWBORN, D., RICHARDSON, M. & BAINES, D. 2017. Does rotational heather burning increase red grouse abundance and breeding success on moors in northern England? *Wildlife Biology,* wlb.00276**,** 1-12.

ROOS, S., DONALD, C., DUGAN, D., HANCOCK, M. H., O'HARA, D., STEPHEN, L. & GRANT, M. 2016. Habitat associations of young Black Grouse Tetrao tetrix broods. *Bird Study,* 63**,** 203-213.

ROSENBURGH, A., ALDAY, J. G., HARRIS, M. P., ALLEN, K. A., CONNOR, L., BLACKBIRD, S. J., EYRE, G. & MARRS, R. H. 2013. Changes in peat chemical properties during post-fire succession on blanket bog moorland. *Geoderma,* 211**,** 98-106.

RSPB. 2016. *The Walshaw Effect - Northern England's protected blanket bogs RSPB complaint to the European Commission - update April 2016* [Online]. Sandy, Bedfordshire: Royal Society for the Protection of Birds. Available: https://www.rspb.org.uk/globalassets/downloads/documents/campaigning-for-nature/case-studies/rspb-summary-walshaw-moor-april-2016.pdf [Accessed 8/12/2018].

SANTANA, V. M., ALDAY, J. G., LEE, H., ALLEN, K. A. & MARRS, R. H. 2015. Prescribed-burning vs. wildfire: management implications for annual carbon emissions along a latitudinal gradient of <i>Calluna vulgaris</i>-dominated vegetation. *Biogeosciences Discuss.,* 2015**,** 17817-17849.

SANTANA, V. M., ALDAY, J. G., LEE, H., ALLEN, K. A. & MARRS, R. H. 2016. Modelling Carbon Emissions in Calluna vulgaris–Dominated Ecosystems when Prescribed Burning and Wildfires Interact. *PLOS ONE,* 11**,** e0167137.

SANTANA, V. M. & MARRS, R. H. 2016. Models for predicting fire ignition probability in graminoids from boreo–temperate moorland ecosystems. *International Journal of Wildland Fire,* 25**,** 679-684.

SHEPHERD, M., LABADZ, J., CAPORN, S., CROWLE, A., GOODISON, R., REBANE, M. & WATERS, R. 2013. *Restoration of degraded blanket bog,* Peterborough, UK, Natural England evidence review NEER003.

SHORTEN, A. & SHORTEN, B. 2013. What is meta-analysis? *Evidence Based Nursing,* 16**,** 3.

SMOKOROWSKI, K. & RANDALL, R. 2017. Cautions on using the Before-After-Control-Impact design in environmental effects monitoring programs. *Facets,* 2**,** 212-232.

SOTHERTON, N., BAINES, D. & AEBISCHER, N. J. 2017. An alternative view of moorland management for Red Grouse Lagopus lagopus scotica. *Ibis,* 159**,** 693-698.

STONE, D. 2013. *Natural England Evidence Reviews: guidance on the development process and methods,* Peterborough, UK, Natural England evidence review NEER001.

SUTHERLAND, W. J., PULLIN, A. S., DOLMAN, P. M. & KNIGHT, T. M. 2004. The need for evidence-based conservation. *Trends in ecology & evolution,* 19**,** 305-308.

SWINDLES, G. T., MORRIS, P. J., WHEELER, J., SMITH, M. W., BACON, K. L., TURNER, T. E., HEADLEY, A. & GALLOWAY, J. M. 2016. Resilience of peatland ecosystem services over millennial timescales: evidence from a degraded British bog. *Journal of Ecology,* 104**,** 621-636.

SWINDLES, G. T., TURNER, T. E., ROE, H. M., HALL, V. A. & REA, H. A. 2015. Testing the cause of the Sphagnum austinii (Sull. ex Aust.) decline: Multiproxy evidence from a raised bog in Northern Ireland. *Review of Palaeobotany and Palynology,* 213**,** 17-26.

TAYLOR, E. S. 2015. *Impact of fire on blanket bogs: implications for vegetation and the carbon cycle.* PhD, University of Edinburgh.

TAYLOR, N. G., GRILLAS, P. & SUTHERLAND, W. J. 2018. *Peatland Conservation: Global Evidence for the Effects of Interventions to Conserve Peatland Vegetation,* Cambridge, UK, Synopses of Conservation Evidence Series. University of Cambridge.

THACKER, J., YALLOP, A. R. & CLUTTERBUCK, B. 2014. IPENS 055. Burning in the English uplands: a review, reconciliation and comparison of results of Natural England's burn monitoring: 2005–2014. Peterborough, UK: Natural England.

THOMPSON, P. S., DOUGLAS, D. J., HOCCOM, D. G., KNOTT, J., ROOS, S. & WILSON, J. D. 2016. Environmental impacts of high-output driven shooting of Red Grouse Lagopus lagopus scotica. *Ibis,* 158**,** 446-452.

TURNER, T. E. & SWINDLES, G. T. 2012. Ecology of Testate Amoebae in Moorland with a Complex Fire History: Implications for Ecosystem Monitoring and Sustainable Land Management. *Protist,* 163**,** 844-855.

VANE, C. H., RAWLINS, B. G., KIM, A. W., MOSS-HAYES, V., KENDRICK, C. P. & LENG, M. J. 2013. Sedimentary transport and fate of polycyclic aromatic hydrocarbons (PAH) from managed burning of moorland vegetation on a blanket peat, South Yorkshire, UK. *Science of the total environment,* 449**,** 81-94.

VELLE, L. G., NILSEN, L. S., NORDERHAUG, A. & VANDVIK, V. 2014. Does prescribed burning result in biotic homogenization of coastal heathlands? *Global Change Biology,* 20**,** 1429-1440.

VELLE, L. G. & VANDVIK, V. 2014. Succession after prescribed burning in coastal Calluna heathlands along a 340-km latitudinal gradient. *Journal of Vegetation Science,* 25**,** 546-558.

WALKER, T. N., GARNETT, M. H., WARD, S. E., OAKLEY, S., BARDGETT, R. D. & OSTLE, N. J. 2016. Vascular plants promote ancient peatland carbon loss with climate warming. *Global Change Biology,* 22**,** 1880-1889.

WARD, S. E., OSTLE, N. J., OAKLEY, S., QUIRK, H., HENRYS, P. A. & BARDGETT, R. D. 2013. Warming effects on greenhouse gas fluxes in peatlands are modulated by vegetation composition. *Ecology Letters,* 16**,** 1285-1293.

WARD, S. E., OSTLE, N. J., OAKLEY, S., QUIRK, H., STOTT, A., HENRYS, P. A., SCOTT, W. A. & BARDGETT, R. D. 2012. Fire accelerates assimilation and transfer of photosynthetic carbon from plants to soil microbes in a northern peatland. *Ecosystems,* 15**,** 1245-1257.

WEI, X., HAYES, D. J., FRAVER, S. & CHEN, G. 2018. Global Pyrogenic Carbon Production During Recent Decades Has Created the Potential for a Large, Long-Term Sink of Atmospheric CO2. *Journal of Geophysical Research: Biogeosciences,* 123**,** 3682-3696.

WHITEHEAD, S. C. & BAINES, D. 2018. Moorland vegetation responses following prescribed burning on blanket peat. *International Journal of Wildland Fire,* 27**,** 658-664.

WHITTINGHAM, M., PERCIVAL, S. & BROWN, A. 2000. Time budgets and foraging of breeding golden plover Pluvialis apricaria. *Journal of Applied Ecology,* 37**,** 632-646.

WHITTINGHAM, M. J., PERCIVAL, S. M. & BROWN, A. F. 2002. Nest-site selection by golden plover: why do shorebirds avoid nesting on slopes? *Journal of Avian Biology,* 33**,** 184-190.

WORRALL, F., CLAY, G. D. & MAY, R. 2013a. Controls upon biomass losses and char production from prescribed burning on UK moorland. *Journal of environmental management,* 120**,** 27-36.

WORRALL, F., ROWSON, J. & DIXON, S. 2013b. Effects of managed burning in comparison with vegetation cutting on dissolved organic carbon concentrations in peat soils. *Hydrological Processes,* 27**,** 3994-4003.

YOUNG, D. M., BAIRD, A. J., CHARMAN, D. J., EVANS, C. D., GALLEGO-SALA, A. V., GILL, P. J., HUGHES, P. D. M., MORRIS, P. J. & SWINDLES, G. T. 2019. Misinterpreting carbon accumulation rates in records from near-surface peat. *Scientific Reports,* 9**,** 17939.

Appendix A: Peer review comments

Below are the peer review comments provided by Dr Gavin B. Stewart (Newcastle University) on the original draft of this review (Italicised text). Also shown are the responses of Dr Mark A. Ashby (Blue text).

Overall comments

Ashby and colleagues review burning management post Glaves to provide a summary of the most recent evidence. The review scope is problematic in evidence synthesis terms- with questions based on an extant narrative review where specific questions are not always fully defined and are very broad particularly with respect to outcomes. Nonetheless the author's provide a review which has elements of systematic review including use of inclusion criteria, search strategy, and critical appraisal. A protocol was not utilised but this is not yet universal in the field of environmental review. I would judge that despite this, the acquisition of evidence was demonstrably unbiased, repeatable and of sufficient sensitivity to draw valid conclusions. A repeatable critical appraisal was included which provided a useful dichotomy of evidence based on causation despite some problems with spatio-temporal relationships which are often hard to address in this domain. An evidence synthesis was undertaken addressing a series of a priori questions. Narrative synthesis was used and is justified by review scope and high heterogeneity amongst studies in terms of methods, taxon and outcomes. The narrative synthesis and evidence summaries provide transparent but not repeatable statements regarding evidence alongside components of a very useful database of study characteristics. Extending this database with explicit information about study outcomes, judgements about direction, size and precision of effects, and habitat would allow more nuanced judgements about strength of evidence. Deficiencies in the evidence-base are recognised in implications for research but not fully articulated in the synthesis or evidence summaries. There are therefore considerable uncertainties in the statements about the effects of burning management in this review, as there are in primary studies and other reviews on the topic. The transparency with which the review has been undertaken and provision of data provide important foundational steps for the development of a more robust evidence-base. The potential for open science to provide a collaborative mechanism to develop evidence-informed policy in this contested environmental space should be recognised and embraced by researchers, policy makers and stakeholders alike.

Specific comments on the introduction, methods and results, general comments on the evidence synthesis and implications for research

L12 paragraph preceding: I understand the brief is to review post Glaves literature- But the science objective of interest in a policy context is to understand if the new evidence changes the conclusions one would draw from the cumulative evidence-base. Being more explicit about the controversy and the policy context might be helpful? Reference to any tender briefs would improve transparency.

I have been more explicit about why I was contracted by the Moorland Association, and I have also been more explicit about the controversy and policy context. Furthermore, while I have mentioned that "the science objective of interest in a policy context is to understand if the new evidence changes the conclusions one would draw from the cumulative evidence-base", I have outlined that this can only be done by reviewing the entire evidence base. However, after consultation with Natural England, they suggested we do not go over old ground (i.e. the evidence in Glaves et al., 2013), but instead review the evidence that has emerged since 2012.

L18 inclusion criteria: The inclusion criteria are very broad- with some specific questions defining outcomes more precisely replicating the questions posed by the glaves review. However, more details of both population and intervention are needed to derive repeatable inclusion criteria (are there habitat, taxonomic or geographical restrictions on inclusion, is accidental burning relevant, how is experimental burning treated, is post burn recovery relevant). I note that greater detail is provided later in the review but this would be better consolidated and defined here. Greater definition of outcome measures and defining primary and secondary outcomes would reduce the probability of selective reporting and HARKING. Such definitions would be mandatory in a medical setting, ideally specified a priori.

I have moved the inclusion criteria to section 1.1.

L62 This is a commendable objective. Providing a transparent and accessible data-base of relevant studies is very valuable contribution to moving the debate on the pros and cons of prescribed burning forward; more so as this includes the oft neglected critical appraisal necessary to inform overall strength of evidence assessments. So called "living reviews" are emerging in some domains, allowing for continuous updating of important evidence-bases as knowledge is accrued. The database provided here and the Glaves review could form the precursor of such a living review to inform upland land management decisions across GB.

I have added an additional sentence alluding to the potential of both reviews providing the basis of a 'living review' on the impacts of managed burning on upland peatlands in the UK.

L70 Short explicit paragraph on differences and rationale

I have changed this short passage to: "This review attempted to use a similar methodology to Glaves et al. (2013) but, due to several reasons (e.g. logistics), this could not always be achieved. Significant departures from the Glaves et al. (2013) methodology are highlighted throughout the subsequent sections". Thus, I will describe significant differences in methodology throughout the methods section.

L143 Short explanation of how much or how little redundancy there was between articles from the search and articles from included reviews would help define the sensitivity of the search (put this in the results) The detail is provided in the supplementary material which is gold standard in terms of search inclusion transparency, but the salient details need reporting.

I have inserted this information in Table 4.

Table 2 – superfluous?? move to appendix?

I have moved this Table to the appendices.

L173- these inclusion criteria need to be specified earlier (see comment re L18)

I have moved the inclusion criteria to section 1.1.

L233 [General comment] Notwithstanding specific criticisms regarding outcome definition, the acquisition of evidence for the review appears sound and conforms with bias minimisation strategies employed in contemporaneous meta-analyses and reviews in the environmental field. Information specialists would no doubt advocate use of a broader more sensitive search and multiple reviewers but experience of reviews in this field and emerging evidence from rapid reviews suggest the bias associated with less exhaustive searches and single reviewers is minimal.

L251- Use of subjective domain based assessment for study appraisal (sensu glaves) is a standard approach to considering risk of bias in many evidence synthesis contexts. The score *based system you have utilised is more repeatable than the overall domain based-judgement but no less subjective. Suggest rephrasing to make this more apparent.*

I have rephrased to highlight that both approaches are subjective and, therefore, open to criticism. However, the approach used in this review is clearer and more repeatable.

L253- I really like the idea of identifying gold standard studies and think this is very useful. However- I don't think that there is a single optimal spatio-temporal scale (landscape level management manipulations). Rather, this is linked to outcomes. e.g. changes in sphagnum abundance may be optimally measured at a patch scale especially if considering single species; whereas bird population abundance is likely to be more usefully measured at a larger scale? Identifying the spatio-temporal thresholds of gold standard studies would be a great suggestion for further work- but here represents a study characteristic rather than a quality component per se. Conversely, consideration of causation is a critical and oft-neglected element of assessing the strength of evidence. Ascertaining how (or if) only considering evidence with strong causal claims, changes the evidence-base should be a key focus of this review/and/or future work. There is a general consensus in clinical medicine that policy should be informed by a single (or few) studies with robust inference (despite generalisability concerns) rather than a larger number of studies where causation cannot be attributed (garbage in, garbage out). The trade-off here is that studies with strong causal claims (randomised, replicated studies) are difficult to implement especially at the larger spatio-temporal scales required to capture management effects or ecosystem process.

I have replaced "Gold standard" with "Very high quality". I have also made this category only obtainable by passing all 16 of the critical appraisal questions.

Tables 3&4. The questions posed are unambiguous and helpful in characterising study methodology. The value judgements underpinning assessment of risk of bias in Table 4 are fully transparent and have a strong rationale grounded in ability to ascribe causation. However, studies that are very informative but at high risk of bias will be described as low quality. e.g. well conducted paleoecology based on peatcores. Rephrasing in terms of risk of bias and nuanced interpretation with discussion of how study methods impact conclusions accompanying the bifurcation of data into causality classes might be useful modifications.

I have made it clear that the quality rating is primarily an assessment of a studies ability to ascribe causation. I have also highlighted that, whilst being designated as low quality, paleoecology studies are extremely informative. However, due to the diminished capability of such studies to ascribe causation, they should be considered as the basis for further investigation (e.g. via experimentation).

L307. Consider addition of PRISMA diagram (mandatory in medical domains, increasingly prevalent in environmental fields).

Table 4 now serves the same function as a PRISMA diagram because it has been modified to include the number of articles obtained during each search method, the number of duplicates removed, the number of articles accepted at each stage of screening and the number of accepted articles obtained using each search method.

L318. Succinct and discriminatory study description. It might be worth defining the design terminology and relating to risk of bias? Maybe an additional column or two in table 8?

I have not added extra columns, but I have changed the table title to this: "The number of accepted studies by type of study. In general, experimental studies (i.e. controlled trials) have the lowest risk of bias (Hurlbert, 1984; Smokorowski and Randall, 2017). The randomisation of treatments and collection of baseline data (i.e. a before-and-after study) further reduces bias (ibid)".

Evidence synthesis

L1144 [Evidence synthesis narrative] The evidence synthesis is well structured considering study findings in relation to the original review questions stratified by risk of bias. However, the value judgements, diverse study designs and heterogeneous outcomes measured by the studies make statements about the overall evidence problematic. Arguably, these problems are common to all narrative reviews but the breadth of evidence considered and the contested policy context exacerbate the issue. In my view the five problems with the approach should be elucidated and the uncertainty arising from them acknowledged.

1) *The value judgements about the evidence are transparent and the arguments underpinning them are clear, but there is a multiverse of alternative arguments and value judgements. It is problematic to consider studies too diverse to be formally combined in a meta-analysis as consistent in effect especially where precision and effect magnitude for individual studies aren't ascertained. Such evidence statements should be defined explicitly as highly uncertain or unpacked further in my view.*

   I have discussed the uncertainty of the evidence statements at the beginning of section 5.

2) *There are frequently differences between the author's conclusions and the data presented in primary studies. This can arise because authors selectively report or emphasise some results rather than others, choose particular end-points or methods of analysis. The current review relies too heavily on the author's interpretation of the data rather than utilising studies simply as a means to acquire data for synthesis. This can be illustrated with the hard hill data for Sphagnum response to burning [based on ecn dataset]. Despite representing the best evidence available on sphagnum response to burning it is possible to present and interpret the data from this monitoring in multiple ways. Six species of sphagnum are recorded in the data-set but despite use of an objective outcome measure rather than subjective cover and high intensity monitoring, data is too sparse for five species to draw any conclusions at all regarding changing species composition or diversity. (see figure 1). Note that this point is made in the review research recommendations but not in the evidence synthesis or summary. There is a large volume of data on Sphagnum capillifolium, and it is therefore possible to make many different claims about the effects of burning on this species depending on choice of endpoint and comparison. However, the variance in the data make it abundantly clear, that predicting differences in treatments with certainty is impossible (figure 2). One definition of reliable evidence,-is that a hypothetical future study would almost certainly not change your conclusions. This is clearly not the case here and contrasts with the conclusion in the evidence summary 5.13 that 12 consistent studies allow inference. This example illustrates the problem of relying on authors interpretations of evidence.*

   I have addressed this by reporting study findings rather than author conclusions.

3) *A related problem to relying on the author's interpretation is that there is no consideration of effect magnitude or precision when combining information across studies. One large precise study with a negative effect could outweigh any number of smaller positive studies, despite appearing to be an outlier when summing across studies numerically. This problem of "vote counting" is well known but is very difficult to address unless meta-analysis can be undertaken.*
4) *The fact that ecological studies frequently measure different things even when exploring the same construct has frustrated those involved in synthesis for some time (cf http://www.comet-initiative.org/Studies/Details/1278). Combining surrogate*

outcomes with directly relevant measures across studies adds hugely to uncertainty and this requires more acknowledgement and unpicking.

5) *Habitat type (specifically deep v shallow peats) is a major potential reason for heterogeneity in effect with important policy implications. This is considered for some outcomes but requires standardised reporting and treatment across all the questions addressed by the review. If it is unclear what habitat or habitats were investigated in a specific study this should be specified.*

   All but two of the studies were conducted on deep peat (either exclusively or areas of deep peat areas constituted part of the area from which data were collected). However, I have noted the habitat type of each study within the "Supplementary Database 3.xlxs".

Fully addressing all of these problems is clearly resource intensive, beyond the scope of narrative review and requires changes to the way we fund and undertake primary research as well as our interpretation and synthesis methods. Nonetheless, there are a range of options for mitigating some of the uncertainty engendered. The simplest option would be to include discussion of these problems and add caveats regarding uncertainty to the textual statements in the synthesis and evidence summaries. More usefully, the supplementary material detailing study inclusion, characteristics and methodology could be combined and extended to include study outcomes (as stated by the author) and habitat type. This could be the basis of a relational database, but even simple pivot tables could be used to provide standardised templates to underpin both the textual synthesis and evidence summaries. Including categorical variables defining the information content (study effect, direction, precision) and directness of outcomes would provide a means of attempting to address the vote counting and surrogate outcome problems. However, some analysts would likely dispute the value of the endeavour given the high subjectivity.

Research recommendations

The research recommendations appear thoughtful and sensible, but it is not clear how they relate to uncertainties in the evidence base. Directly and explicitly linking the need for research to uncertainty related to i) poor causation/confounding ii) imprecision iii) inconsistency iv) indirectness and v) potential bias would be useful. These form elements of *the GRADE framework widely utilised in medicine and applied increasingly to environmental contexts. Some form of prioritisation would also be useful given that this review can usefully highlight the deficiencies in the current evidence-base and has a potentially useful role in shaping the future research agenda.*

Implications for policy

There were no implications for policy

Whilst uncertainty remains very high due to deficiencies in the evidence-base, implications for policy should be discussed. These might be more easily discernible, following further development of a database if this is pursued.

I have provided a brief discussion about policy implications within section 6.9.

Supplementary material

Supplementary material regarding the search and study inclusion is extensive and high quality

Improved formatting of supplementary material, provision of .txt and .csv files would be desirable

I have improved supplementary material formatting. However, I have only supplied supplementary material as .xlxs files because, due to the use of multiple tabs, .txt and .csv files are not appropriate.

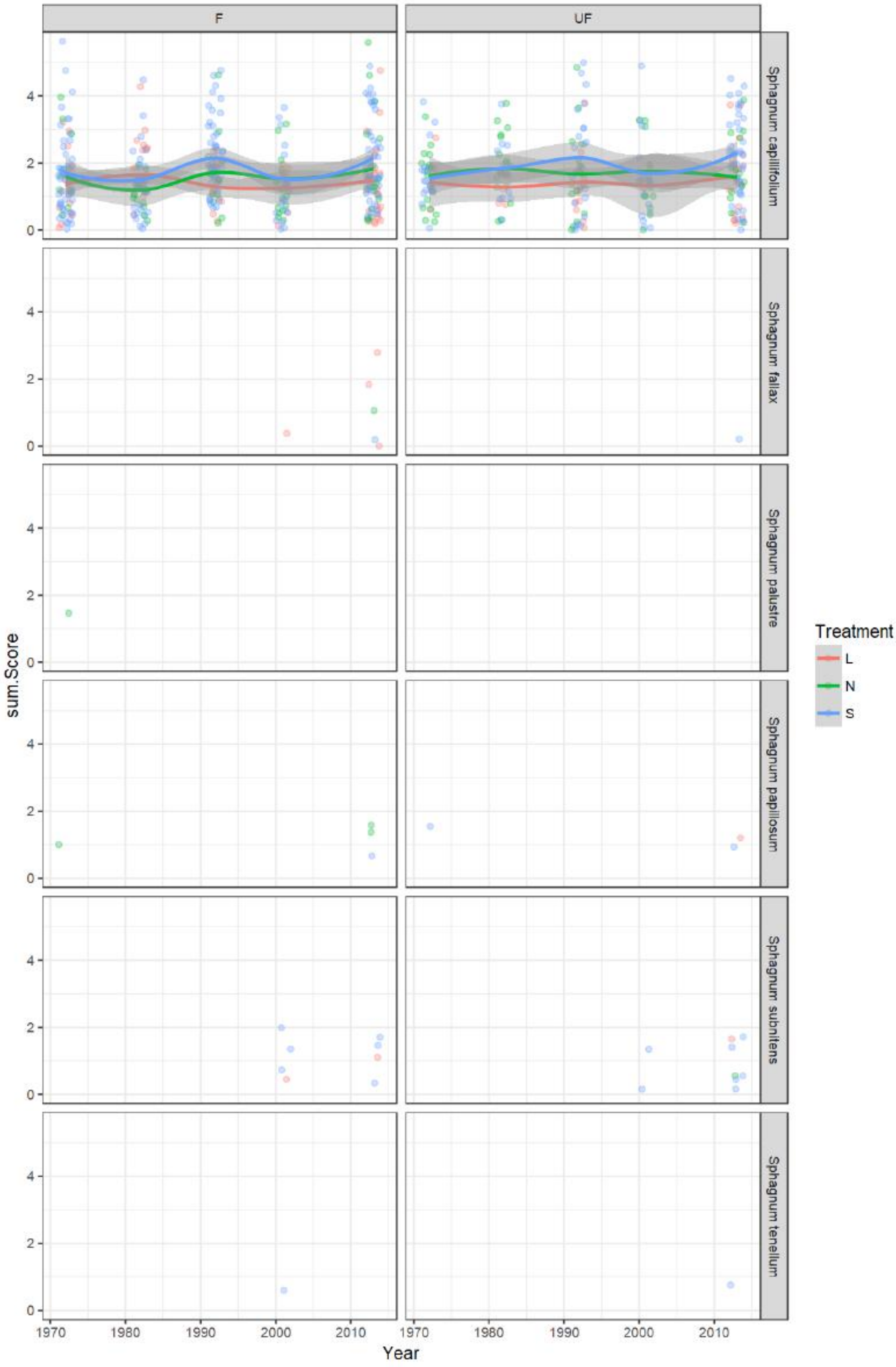
I advocate for development of a database to inform the narrative synthesis and evidence summaries in the review.

I have stated this explicitly within the review objectives in section 1.1.

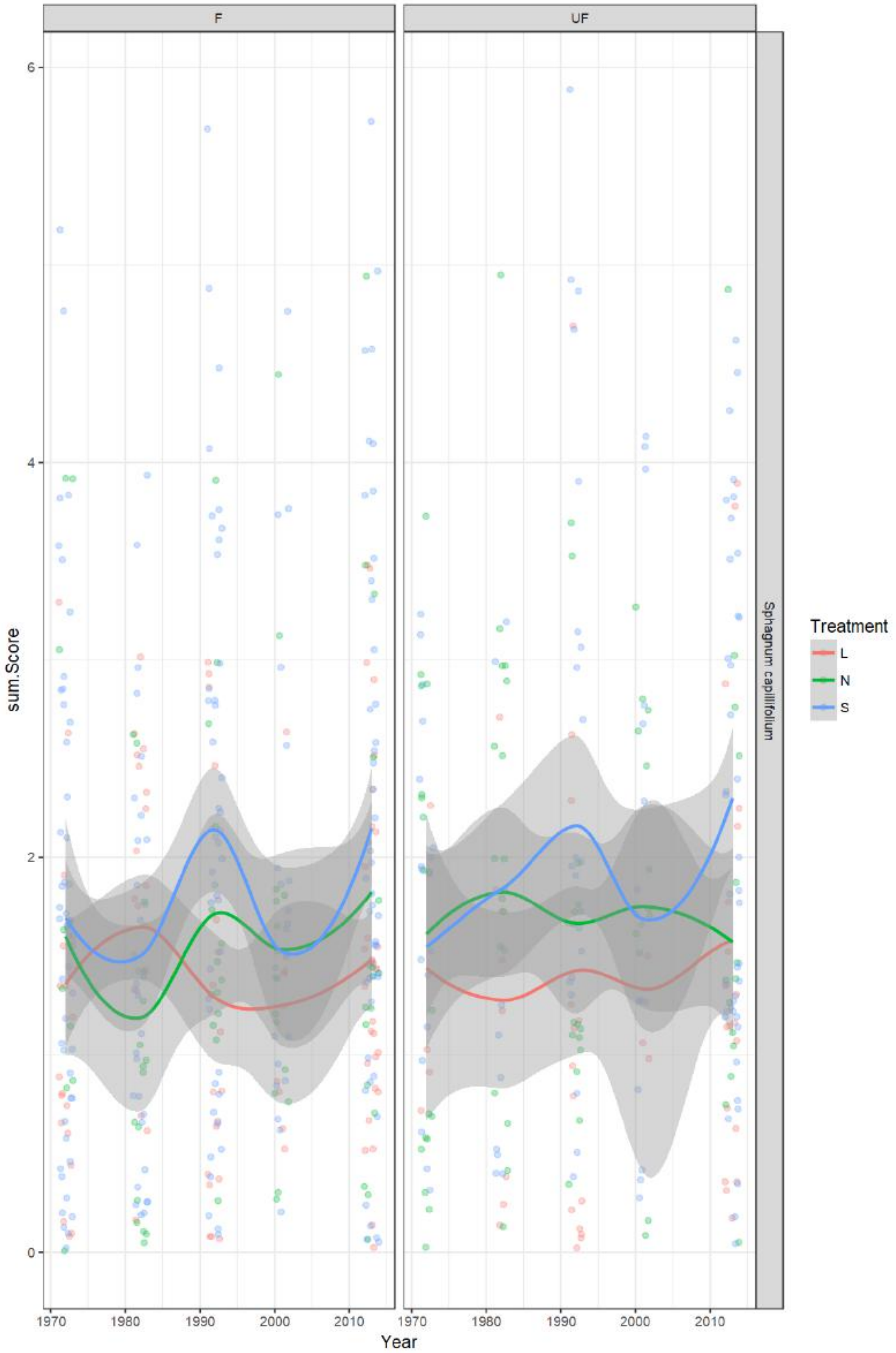
***Bias statement**. I have attempted to provide a full and fair appraisal of the evidence synthesis undertaken by the review team. I have focused on evidence synthesis methodology not the details of ecology, geology or hydrology. I have previously worked (and continue to work) not only on evidence synthesis but also upland management. Funders include NERC, Natural England, RSPB, and the Moorland Association (who have paid for this review). I have personal friends and collaborators who have divergent views on upland policy. I remain committed to the principles of open science and robust evidence synthesis including critical* *appraisal, and believe that a consensus on how to manage British uplands can be found and implemented based upon sound science.*

Gavin B Stewart

April 2020



The figure above graphs *Sphagnum* (various species) pin-frame data from the Hard Hill experimental plots. N = unburnt since 1954, L = burnt every 20 years, S = burnt every 10 years. F = fenced, UF = unfenced.



The figure above graphs *Sphagnum capillifolium* pin-frame data from the Hard Hill experimental plots. N = unburnt since 1954, L = burnt every 20 years, S = burnt every 10 years. F = fenced, UF = unfenced.

Appendix B: Relevant articles not included in this review

The articles in the table below were not included within this review because they are not primary empirical investigations or, if they were, they did not meet all the review inclusion criteria. Nevertheless, they are included here because they are relevant to answering or interpreting the overarching review question and sub-questions.

Reference	**Reference type**
ALONSO, I., WESTON, K., GREGG, R. & MORECROFT, M. 2012. Carbon storage by habitat: Review of the evidence of the impacts of management decisions and condition of carbon stores and sources. Natural England Research Report NERR043. Peterborough, UK: Natural England.	Literature Review
ANDERSEN, R., CHAPMAN, S. J. & ARTZ, R. R. E. 2013. Microbial communities in natural and disturbed peatlands: A review. Soil Biology & Biochemistry, 57, 979-994.	Literature Review
ASHBY, M. A. & HEINEMEYER, A. 2019. Prescribed burning impacts on ecosystem services in the British uplands: A methodological critique of the EMBER project. Journal of Applied Ecology, 00, 1-9.	Comment Paper
ASHBY, M. A. & HEINEMEYER, A. 2019. 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). EcoEvoRxiv, October 31.	Comment Paper
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., THOM, T., WADDINGTON, J. M. & YOUNG, D. M. 2019. Validity of managing peatlands with fire. Nature Geoscience, 12, 884-885.	Comment Paper
BIXBY, R. J., COOPER, S. D., GRESSWELL, R. E., BROWN, L. E., DAHM, C. N. & DWIRE, K. A. 2015. Fire effects on aquatic ecosystems: an assessment of the current state of the science. Freshwater Science, 34, 1340-1350.	Literature Review
BROWN, L. E. & HOLDEN, J. 2019. Contextualising UK moorland burning studies: geographical versus potential sponsorship-bias effects on research conclusions. bioRxiv, 731117.	Comment Paper
BROWN, L. E., HOLDEN, J. & PALMER, S. M. 2016. Moorland vegetation burning debates should avoid contextomy and anachronism: a comment on Davies et al. (2016). Philosophical Transactions of the Royal Society B-Biological Sciences, 371.	Comment Paper

Reference	Reference type
BROWN, L. E., HOLDEN, J., PALMER, S. M., JOHNSTON, K., RAMCHUNDER, S. J. & GRAYSON, R. 2015. Effects of fire on the hydrology, biogeochemistry, and ecology of peatland river systems. Freshwater Science, 34, 1406-1425.	Literature Review
DAVIES, G. M. 2013. Understanding Fire Regimes and the Ecological Effects of Fire. In: BELCHER, C. M. (ed.) Fire phenomena and the Earth system: an interdisciplinary guide to fire science. London, UK: Wiley.	Book Section
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., MCMORROW, J. & 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.	Literature Review
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., MCMORROW, J. & VANDVIK, V. 2016. Informed debate on the use of fire for peatland management means acknowledging the complexity of socio-ecological systems. Nature Conservation-Bulgaria, 59-77.	Comment Paper
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., MCMORROW, J. & VANDVIK, V. 2016. The peatland vegetation burning debate: keep scientific critique in perspective. A response to Brown et al. and Douglas et al. Philosophical Transactions of the Royal Society B-Biological Sciences, 371.	Comment Paper
DAVIES, G. M., STOOF, C. R., KETTRIDGE, N. & GRAY, A. 2016. Comment on: Vegetation burning for game management in the UK uplands is increasing and overlaps spatially with soil carbon and protected areas. Biological Conservation, 195, 293-294.	Comment Paper
DOUGLAS, D. J. T., BUCHANAN, G. M., THOMPSON, P. & WILSON, J. D. 2016. The role of fire in UK upland management: the need for informed challenge to conventional wisdoms: a comment on Davies *et al.* (2016). Philosophical Transactions of the Royal Society B: Biological Sciences, 371, 20160433.	Comment Paper
DOUGLAS, D. J., BUCHANAN, G. M., THOMPSON, P., SMITH, T., COLE, T., AMAR, A., FIELDING, D. A., REDPATH, S. M. & WILSON, J. D. 2016. Reply to comment on: vegetation burning for game management in the UK uplands is increasing and overlaps spatially with soil carbon and protected areas. Biological Conservation, 195, 295-296.	Comment Paper

Reference	Reference type
EVANS, C. D., BAIRD, A. J., GREEN, S. M., PAGE, S. E., PEACOCK, M., REED, M. S., ROSE, N. L., STONEMAN, R., THOM, T. J., YOUNG, D. M. & GARNETT, M. H. 2019. 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 A. Heinemeyer, Q. Asena, W. L. Burn and A. L. Jones (Geo: Geography and Environment 2018; e00063). Geo-Geography and Environment, 6.	Comment Paper
GILLINGHAM, P., STEWART, J. & BINNEY, H. 2016. The historic peat record: Implications for the restoration of blanket bog, Natural England Evidence Review, Number 011.	Systematic Review
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.	Literature Review
HEINEMEYER, A. & VALLACK, H. W. 2015. Literature review on: potential techniques to address heather dominance and help support 'active' Sphagnum supporting peatland vegetation on blanket peatlands and identify practical management options for experimental testing. York, UK: University of York draft report to Defra and Natural England.	Literature Review
HEINEMEYER, A., BURN, W. L., ASENA, Q., JONES, A. L. & ASHBY, M. A. 2019. 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-Geography and Environment, 6.	Comment Paper
JONES, L., STEVENS, C., ROWE, E. C., PAYNE, R., CAPORN, S. J. M., EVANS, C. D., FIELD, C. & DALE, S. 2017. Can on-site management mitigate nitrogen deposition impacts in non-wooded habitats? Biological Conservation, 212, 464-475.	Literature Review
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., SANTANA, V., LEE, H., HALSALL, K. & CHIVERRELL, R. C. 2019. Reply to: Validity of managing peatlands with fire. Nature Geoscience, 12, 886-888.	Comment Paper
PARRY, L. E., HOLDEN, J. & CHAPMAN, P. J. 2014. Restoration of blanket peatlands. Journal of Environmental Management, 133, 193-205.	Literature Review
SOTHERTON, N., BAINES, D. & AEBISCHER, N. J. 2017. An alternative view of moorland management for Red Grouse Lagopus lagopus scotica. Ibis, 159, 693-698.	Comment Paper

Reference	Reference type
SWINDLES, G. T., MORRIS, P. J., MULLAN, D. J., PAYNE, R. J., ROLAND, T. P., AMESBURY, M. J., LAMENTOWICZ, M., TURNER, T. E., GALLEGO-SALA, A., SIM, T., BARR, I. D., BLAAUW, M., BLUNDELL, A., CHAMBERS, F. M., CHARMAN, D. J., FEURDEAN, A., GALLOWAY, J. M., GAŁKA, M., GREEN, S. M., KAJUKAŁO, K., KAROFELD, E., KORHOLA, A., LAMENTOWICZ, Ł., LANGDON, P., MARCISZ, K., MAUQUOY, D., MAZEI, Y. A., MCKEOWN, M. M., MITCHELL, E. A. D., NOVENKO, E., PLUNKETT, G., ROE, H. M., SCHONING, K., SILLASOO, Ü., TSYGANOV, A. N., VAN DER LINDEN, M., VÄLIRANTA, M. & WARNER, B. 2019. Widespread drying of European peatlands in recent centuries. Nature Geoscience, 12, 922-928.	Primary Research
THOMPSON, P. S., DOUGLAS, D. J. T., HOCCOM, D. G., KNOTT, J., ROOS, S. & WILSON, J. D. 2016. Environmental impacts of high-output driven shooting of Red Grouse Lagopus lagopus scotica. Ibis, 158, 446-452.	Comment Paper
TURETSKY, M. R., BENSCOTER, B., PAGE, S., REIN, G., VAN DER WERF, G. R. & WATTS, A. 2015. Global vulnerability of peatlands to fire and carbon loss. Nature Geoscience, 8, 11-14.	Literature Review
WERRITTY, A., PAKEMAN, R. J., SHEDDEN, C., SMITH, A. & WILSON, J. D. 2015. A Review of Sustainable Moorland Management. Battleby: Report to the Scientific Advisory Committee of Scottish Natural Heritage.	Literature Review
YALLOP, A. R., CLUTTERBUCK, B. & THACKER, J. I. 2012. Changes in water colour between 1986 and 2006 in the headwaters of the River Nidd, Yorkshire, UK: a critique of methodological approaches and measurement of burning management. Biogeochemistry, 111, 97-103.	Comment Paper
YOUNG, D. M., BAIRD, A. J., CHARMAN, D. J., EVANS, C. D., GALLEGO-SALA, A. V., GILL, P. J., HUGHES, P. D. M., MORRIS, P. J. & SWINDLES, G. T. 2019. Misinterpreting carbon accumulation rates in records from near-surface peat. Scientific Reports, 9, 17939.	Primary Research

Appendix C: Duplicate removal methodology

The eight-step method used to remove duplicate references. This method was taken and modified from Bramer et al. (2016).

Step	EndNote fields	Process of removal
1	Author | Year | Title | Secondary Title (Journal)	After the 'Find Duplicates' tool has been run, close the 'Find Duplicates' window and press delete to remove all selected duplicates (no manual assessment required).
2	Author | Year | Title | Pages	Same as Step 1.
3	Title | Volume | Pages	After the 'Find Duplicates' tool has been run, close the 'Find Duplicates' window and: A. Manually assess the top references with a blank title or author fields, using ctrl-left click to deselect false duplicates. B. Click on the column heading ''Pages'' to sort all duplicate references by descending order of page numbers. C. Review the top references without page numbers and those with page numbers, starting with number 1 for similar author names. If author names of subsequent references differ, deselect the marked false duplicates with ctrl-left click. D. Remove all selected duplicates by pressing delete.
4	Author | Volume | Pages	After the 'Find Duplicates' tool has been run, close the 'Find Duplicates' window and: A. Repeat stages A-B in Step 3. B. Deselect the top references without page numbers by pressing ctrl-left click on the first highlighted reference and ctrl-shift-left click on the first highlighted reference with a starting page number greater than 1. Remove the remaining selected duplicates by pressing delete.
5	Year | Volume | Issue | Pages	After the 'Find Duplicates' tool has been run, close the 'Find Duplicates' window and: A. Right-click on 'My Groups' > 'Create Group' and then press enter. B. In the group 'Duplicate References', click on the column heading 'Pages' to sort all duplicate references by descending order of page numbers. C. Select all references with page numbers by left-clicking on the top reference while holding shift, and then left-clicking on the last reference with page numbers present. D. Drag the selected references to the just created 'New Group' folder. E. Click on 'New Group'. Then check 'New Group' group for references with just one page and page numbers starting with '1' or with a letter. Select false duplicates from those references and then press delete to remove them from the group (They remain in 'All References' but are not de-duplicated in this step). F. Select one of the references in the 'New Group' folder. Then run the 'Find Duplicates' tool, close the 'Find Duplicates' window and press delete to remove all selected duplicates (no manual assessment required).
6	Title	After the 'Find Duplicates' tool has been run, close the 'Find Duplicates' window and: A. Compare page numbers of consecutive references. If page numbers are present and different, examine journal titles and authors. Deselect false duplicates using ctrl-left click. References with blank pages or pages starting with the '1' are usually true duplicates but check journal titles and author names when in doubt, especially when multiple consecutive blank pages are selected. B. After checking the entire list, remove the remaining selected duplicate references by pressing delete.
7	Author | Year	After the 'Find Duplicates' tool has been run, close the 'Find Duplicates' window. Then, if a true duplicate is found, deselect all references by left-clicking the first true duplicate. Compare subsequent references on page numbers: if two adjacent references have the same page numbers, select the one with the largest record number with ctrl-left click. After checking the complete list, remove the remaining selected references by pressing delete.
8	Not Applicable	Finally, sort all remaining references by title (A-Z) and manually scan for and remove duplicates.

Appendix D: The articles included within this review

Reference	Reference type
ALDAY, J. G., SANTANA, V. M., LEE, H., ALLEN, K. A. & MARRS, R. H. 2015. Above-ground biomass accumulation patterns in moorlands after prescribed burning and low-intensity grazing. Perspectives in Plant Ecology Evolution and Systematics, 17, 388-396.	Journal
ALLEN, K. A., DENELLE, P., RUIZ, F. M. S., SANTANA, V. M. & MARRS, R. H. 2016. Prescribed moorland burning meets good practice guidelines: A monitoring case study using aerial photography in the Peak District, UK. Ecological Indicators, 62, 76-85.	Journal
BLUNDELL, A. & HOLDEN, J. 2015. Using palaeoecology to support blanket peatland management. Ecological Indicators, 49, 110-120.	Journal
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.	Report
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.	Journal
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.	Journal
BUCHANAN, G. M., PEARCE-HIGGINS, J. W., DOUGLAS, D. J. T. & GRANT, M. C. 2017. Quantifying the importance of multi-scale management and environmental variables on moorland bird abundance. Ibis, 159, 744-756.	Journal
CALLADINE, J., CRITCHLEY, C. N. R., BAKER, D., TOWERS, J. & THIEL, A. 2014. Conservation management of moorland: a case study of the effectiveness of a combined suite of management prescriptions which aim to enhance breeding bird populations. Bird Study, 61, 56-72.	Journal
CHAMBERS, F. M., CLOUTMAN, E. W., DANIELL, J. R. G., MAUQUOY, D. & JONES, P. S. 2013. Long-term ecological study (palaeoecology) to chronicle habitat degradation and inform conservation ecology: an exemplar from the Brecon Beacons, South Wales. Biodiversity and Conservation, 22, 719-736.	Journal
CHAMBERS, F., CROWLE, A., DANIELL, J., MAUQUOY, D., MCCARROLL, J., SANDERSON, N., THOM, T., TOMS, P. & WEBB, J. 2017. Ascertaining the nature and timing of mire degradation: using palaeoecology to assist future conservation management in Northern England. Aims Environmental Science, 4, 54-82.	Journal
CLAY, G. D., WORRALL, F. & AEBISCHER, N. J. 2015. Carbon stocks and carbon fluxes from a 10-year prescribed burning chronosequence on a UK blanket peat. Soil Use and Management, 31, 39-51.	Journal
DALLIMER, M., SKINNER, A. M. J., DAVIES, Z. G., ARMSWORTH, P. R. & GASTON, K. J. 2012. Multiple habitat associations: the role of offsite habitat in determining onsite avian density and species richness. Ecography, 35, 134-145.	Journal
DIXON, S. D., WORRALL, F., ROWSON, J. G. & EVANS, M. G. 2015. Calluna vulgaris canopy height and blanket peat CO2 flux: Implications for management. Ecological Engineering, 75, 497-505.	Journal

Reference	Reference type
DOUGLAS, D. J. T. & PEARCE-HIGGINS, J. W. 2014. Relative importance of prey abundance and habitat structure as drivers of shorebird breeding success and abundance. Animal Conservation, 17, 535-543.	Journal
DOUGLAS, D. J. T., BELLAMY, P. E., STEPHEN, L. S., PEARCE–HIGGINS, J. W., WILSON, J. D. & GRANT, M. C. 2014. Upland land use predicts population decline in a globally near-threatened wader. Journal of Applied Ecology, 51, 194-203.	Journal
DOUGLAS, D. J. T., BERESFORD, A., SELVIDGE, J., GARNETT, S., BUCHANAN, G. M., GULLETT, P. & GRANT, M. C. 2017. Changes in upland bird abundances show associations with moorland management. Bird Study, 64, 242-254.	Journal
DOUGLAS, D. J. T., BUCHANAN, G. M., THOMPSON, P., AMAR, A., FIELDING, D. A., REDPATH, S. M. & WILSON, J. D. 2015. Vegetation burning for game management in the UK uplands is increasing and overlaps spatially with soil carbon and protected areas. Biological Conservation, 191, 243-250.	Journal
FYFE, R. M. & WOODBRIDGE, J. 2012. Differences in time and space in vegetation patterning: analysis of pollen data from Dartmoor, UK. Landscape Ecology, 27, 745-760.	Journal
FYFE, R. M., OMBASHI, H., DAVIES, H. J. & HEAD, K. 2018. Quantified moorland vegetation and assessment of the role of burning over the past five millennia. Journal of Vegetation Science, 29, 393-403.	Journal
GRAU-ANDRES, R., DAVIES, G. M., GRAY, A., SCOTT, E. M. & WALDRON, S. 2018. Fire severity is more sensitive to low fuel moisture content on Calluna heathlands than on peat bogs. Science of the Total Environment, 616, 1261-1269.	Journal
GRAU-ANDRES, R., DAVIES, G. M., WALDRON, S., SCOTT, E. M. & GRAY, A. 2019. Increased fire severity alters initial vegetation regeneration across Calluna-dominated ecosystems. Journal of Environmental Management, 231, 1004-1011.	Journal
GRAU-ANDRES, R., GRAY, A. & DAVIES, G. M. 2017. Sphagnum abundance and photosynthetic capacity show rapid short-term recovery following managed burning. Plant Ecology & Diversity, 10, 353-359.	Journal
GRAU-ANDRES, R., GRAY, A., DAVIES, G. M., SCOTT, E. M. & WALDRON, S. 2019. Burning increases post-fire carbon emissions in a heathland and a raised bog, but experimental manipulation of fire severity has no effect. Journal of Environmental Management, 233, 321-328.	Journal
HEINEMEYER, A., ASENA, Q., BURN, W. L. & JONES, A. L. 2018. Peatland carbon stocks and burn history: Blanket bog peat core evidence highlights charcoal impacts on peat physical properties and long-term carbon storage. Geo-Geography and Environment, 5.	Journal
HEINEMEYER, A., BERRY, R. & SLOAN, T. J. 2019. Assessing soil compaction and micro-topography impacts of alternative heather cutting as compared to burning as part of grouse moor management on blanket bog. Peerj, 7.	Journal
HEINEMEYER, A., VALLACK, H. W., MORTON, P. A., PATEMAN, R., DYTHAM, C., INESON, P., MCCLEAN, C., BRISTOW, C. & PEARCE-HIGGINS, J. W. 2019c. 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 (Appendix by Richard Lindsay). Final Report to Defra on Project BD5104 York, UK,	

Stockholm Environment Institute at the University of York.	
Reference	**Reference type**
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.	Journal
JOHNSTON, K. & ROBSON, B. J. 2015. Experimental effects of ash deposition on macroinvertebrate assemblages in peatland streams. Marine and Freshwater Research, 69, 1681-1691.	Journal
JOHNSTON, K. 2012. Catchment management influences on moorland stream biodiversity. Moors for the future report: MRF610. Edale, UK: Moors for the Future.	Report
LEE, H., ALDAY, J. G., ROSENBURGH, A., HARRIS, M., MCALLISTER, H. & MARRS, R. H. 2013. Change in propagule banks during prescribed burning: A tale of two contrasting moorlands. Biological Conservation, 165, 187-197.	Journal
LITTLEWOOD, N. A., MASON, T. H. E., HUGHES, M., JACQUES, R., WHITTINGHAM, M. J. & WILLIS, S. G. 2019. The influence of different aspects of grouse moorland management on nontarget bird assemblages. Ecology and Evolution, 9, 11089-11101.	Journal
LUDWIG, S. C., AEBISCHER, N. J., BUBB, D., RICHARDSON, M., ROOS, S., WILSON, J. D. & BAINES, D. 2018. Population responses of Red Grouse Lagopus lagopus scotica to expansion of heather Calluna vulgaris cover on a Scottish grouse moor. Avian Conservation and Ecology, 13.	Journal
LUDWIG, S. C., ROOS, S., BUBB, D. & BAINES, D. 2017. Long-term trends in abundance and breeding success of red grouse and hen harriers in relation to changing management of a Scottish grouse moor. Wildlife Biology, 2017.	Journal
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., SANTANA, V., LEE, H., HALSALL, K. & CHIVERRELL, R. C. 2019. Experimental evidence for sustained carbon sequestration in fire-managed, peat moorlands. Nature Geoscience, 12, 108-112.	Journal
MCCARROLL, J., CHAMBERS, F. M., WEBB, J. C. & THOM, T. 2016. Informing innovative peatland conservation in light of palaeoecological evidence for the demise of Sphagnum imbricatum: the case of Oxenhope Moor, Yorkshire, UK. Mires and Peat, 18.	Journal
MCCARROLL, J., CHAMBERS, F. M., WEBB, J. C. & THOM, T. 2016. Using palaeoecology to advise peatland conservation: An example from West Arkengarthdale, Yorkshire, UK. Journal for Nature Conservation, 30, 90-102.	Journal
MCCARROLL, J., CHAMBERS, F. M., WEBB, J. C. & THOM, T. 2017. Application of palaeoecology for peatland conservation at Mossdale Moor, UK. Quaternary International, 432, 39-47.	Journal
MILLIGAN, G., ROSE, R. J., O'REILLY, J. & MARRS, R. H. 2018. Effects of rotational prescribed burning and sheep grazing on moorland plant communities: Results from a 60-year intervention experiment. Land Degradation & Development, 29, 1397-1412.	Journal
MORTON, P. A. & HEINEMEYER, A. 2019. Bog breathing: the extent of peat shrinkage and expansion on blanket bogs in relation to water table, heather management and dominant vegetation and its implications for carbon stock assessments. Wetlands Ecology and Management, 27, 467-482.	Journal
NEWEY, S., MUSTIN, K., BRYCE, R., FIELDING, D., REDPATH, S., BUNNEFELD, N., DANIEL, B. & IRVINE, R. J. 2016. Impact of Management on Avian Communities in the Scottish Highlands. PLOS ONE, 11, e0155473.	Journal

Reference	Reference type
NOBLE, A. 2018. The impacts of prescribed burning on blanket peatland vegetation. PhD, University of Leeds.	PhD thesis
NOBLE, A., CROWLE, A., GLAVES, D. J., PALMER, S. M. & HOLDEN, J. 2019. Fire temperatures and Sphagnum damage during prescribed burning on peatlands. Ecological Indicators, 103, 471-478.	Journal
NOBLE, A., O'REILLY, J., GLAVES, D. J., CROWLE, A., PALMER, S. M. & HOLDEN, J. 2018. Impacts of prescribed burning on Sphagnum mosses in a long-term peatland field experiment. Plos One, 13.	Journal
NOBLE, A., PALMER, S. M., GLAVES, D. J., CROWLE, A. & HOLDEN, J. 2017. Impacts of peat bulk density, ash deposition and rainwater chemistry on establishment of peatland mosses. Plant and Soil, 419, 41-52.	Journal
NOBLE, A., PALMER, S. M., GLAVES, D. J., CROWLE, A. & HOLDEN, J. 2019. Peatland vegetation change and establishment of re-introduced Sphagnum moss after prescribed burning. Biodiversity and Conservation, 28, 939-952.	Journal
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.	Journal
PARRY, L. E., CHAPMAN, P. J., PALMER, S. M., WALLAGE, Z. E., 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.	Journal
ROBERTSON, G. S., NEWBORN, D., RICHARDSON, M. & BAINES, D. 2017. Does rotational heather burning increase red grouse abundance and breeding success on moors in northern England? Wildlife Biology.	Journal
ROOS, S., DONALD, C., DUGAN, D., HANCOCK, M. H., O'HARA, D., STEPHEN, L. & GRANT, M. 2016. Habitat associations of young Black Grouse Tetrao tetrix broods. Bird Study, 63, 203-213.	Journal
ROSENBURGH, A., ALDAY, J. G., HARRIS, M. P. K., ALLEN, K. A., CONNOR, L., BLACKBIRD, S. J., EYRE, G. & MARRS, R. H. 2013. Changes in peat chemical properties during post-fire succession on blanket bog moorland. Geoderma, 211, 98-106.	Journal
SWINDLES, G. T., MORRIS, P. J., WHEELER, J., SMITH, M. W., BACON, K. L., TURNER, T. E., HEADLEY, A. & GALLOWAY, J. M. 2016. Resilience of peatland ecosystem services over millennial timescales: evidence from a degraded British bog. Journal of Ecology, 104, 621-636.	Journal
SWINDLES, G. T., TURNER, T. E., ROE, H. M., HALL, V. A. & REA, H. A. 2015. Testing the cause of the Sphagnum austinii (Sull. ex Aust.) decline: Multiproxy evidence from a raised bog in Northern Ireland. Review of Palaeobotany and Palynology, 213, 17-26.	Journal
TAYLOR, E. S. 2015. Impact of fire on blanket bogs: implications for vegetation and the carbon cycle. PhD, University of Edinburgh.	PhD thesis
TAYLOR, E. S., LEVY, P. E. & GRAY, A. 2017. The recovery of Sphagnum capillifolium following exposure to temperatures of simulated moorland fires: a glasshouse experiment. Plant Ecology & Diversity, 10, 77-88.	Journal
THACKER, J., YALLOP, A. R. & CLUTTERBUCK, B. 2014. IPENS 055. Burning in the English uplands: a review, reconciliation and comparison of results of Natural England's burn monitoring: 2005–2014. Peterborough, UK: Natural England.	Report

TURNER, T. E. & SWINDLES, G. T. 2012. Ecology of Testate Amoebae in Moorland with a Complex Fire History: Implications for Ecosystem Monitoring and Sustainable Land Management. Protist, 163, 844-855.	Journal
Reference	**Reference type**
VANE, C. H., RAWLINS, B. G., KIM, A. W., MOSS-HAYES, V., KENDRICK, C. P. & LENG, M. J. 2013. Sedimentary transport and fate of polycyclic aromatic hydrocarbons (PAH) from managed burning of moorland vegetation on a blanket peat, South Yorkshire, UK. Science of the Total Environment, 449, 81-94.	Journal
VELLE, L. G. & VANDVIK, V. 2014. Succession after prescribed burning in coastal Calluna heathlands along a 340-km latitudinal gradient. Journal of Vegetation Science, 25, 546-558.	Journal
VELLE, L. G., NILSEN, L. S., NORDERHAUG, A. & VANDVIK, V. 2014. Does prescribed burning result in biotic homogenization of coastal heathlands? Global Change Biology, 20, 1429-1440.	Journal
WALKER, T. N., GARNETT, M. H., WARD, S. E., OAKLEY, S., BARDGETT, R. D. & OSTLE, N. J. 2016. Vascular plants promote ancient peatland carbon loss with climate warming. Global Change Biology, 22, 1880-1889.	Journal
WARD, S. E., OSTLE, N. J., OAKLEY, S., QUIRK, H., HENRYS, P. A. & BARDGETT, R. D. 2013. Warming effects on greenhouse gas fluxes in peatlands are modulated by vegetation composition. Ecology Letters, 16, 1285-1293.	Journal
WARD, S. E., OSTLE, N. J., OAKLEY, S., QUIRK, H., STOTT, A., HENRYS, P. A., SCOTT, W. A. & BARDGETT, R. D. 2012. Fire Accelerates Assimilation and Transfer of Photosynthetic Carbon from Plants to Soil Microbes in a Northern Peatland. Ecosystems, 15, 1245-1257.	Journal
WHITEHEAD, S. C. & BAINES, D. 2018. Moorland vegetation responses following prescribed burning on blanket peat. International Journal of Wildland Fire, 27, 658-664.	Journal
WORRALL, F., CLAY, G. D. & MAY, R. 2013. Controls upon biomass losses and char production from prescribed burning on UK moorland. Journal of Environmental Management, 120, 27-36.	Journal
WORRALL, F., ROWSON, J. & DIXON, S. 2013. Effects of managed burning in comparison with vegetation cutting on dissolved organic carbon concentrations in peat soils. Hydrological Processes, 27, 3994-4003.	Journal

Appendix E: Supplementary materials

Supplementary database 1.xlsx – Evidence search results.

Supplementary database 2.xlsx – Evidence screening results.

Supplementary database 3.xlsx – Coding variable data for each study included in this review.

Supplementary database 4.xlsx – Critical appraisal data for each study included in this review.

APPENDIX S1: HOW WE EXPLORED ENVIRONMENTAL DIFFERENCES BETWEEN EMBER SITES AND TREATMENT PLOTS

The EMBER study design

The EMBER project used five burnt and five unburnt upland river catchments (sites) to investigate the impact of prescribed rotational burning on water quality, hydrology, aquatic biodiversity and soils within blanket bog biotopes (Table S1.1) (Brown, Holden & Palmer 2014). All ten catchments are geographically separate: the mean (± standard error of the mean; SEM) distance between burnt and unburnt catchments equals 76. 7 ± 10.9 km, whereas, the mean (± SEM) distance between all catchments equals 79.1 ± 8.3 km. The five burnt catchments were all managed as grouse moors and contained a mosaic of recent burn patches ranging from <1 to 25 years since burning (*ibid*). The five unburnt catchments had a varied history of prescribed rotational burning: Green Burn, Moss Burn and Trout Beck had not been burnt for more than 60 years; whereas, Crowden Little Beck and Oakner Clough had not been burnt for between 30 and 50 years, respectively (Table S1.1) (*ibid*). The predominant soil type across all catchments was blanket peat (*ibid*).

Table S1.1. The burnt and unburnt catchment sites used during the EMBER project.

Management/site	Location
Burnt catchments:	
Bull Clough	Midhope Moor, Peak District
Rising Clough	Derwent Moors, Peak District
Woo Gill	Nidderdale, Yorkshire Dales
Great Eggleshope beck	Teesdale, North Pennines
Lodgegill Sike	Teesdale, North Pennines
Unburnt catchments:	
Crowden Little Beck	Longendale, South Pennines
Green Burn	Teesdale, North Pennines
Moss Burn	Teesdale, North Pennines
Oakner Clough	Marsden Moor, South Pennines
Trout Beck	Teesdale, North Pennines

Twelve study plots were selected within each catchment (burnt plots n = 60; unburnt plots n = 60). In burnt catchments study plots were equally divided into four burning age classes (three replicates per age class): <2 years since burning (B2), 3-4 years since burning (B4), 5-7 years since burning (B7) and >10 years since burning (B10+) (Brown, Holden & Palmer 2014). One replicate of each burning age class was positioned at the top, middle or bottom of a hillslope (*ibid*). Within the unburnt catchments, the 12 study plots were chosen at random, ensuring that there were four replicates located in top, middle or bottom hillslope positions (*ibid*).

Our comparisons of environmental differences between EMBER study catchments and treatment plots

The EMBER study and its associated peer-reviewed articles use different combinations of study catchments and plots depending on the response variable investigated. These different combinations formed the basis of our comparisons between EMBER study catchments and treatment plots. Specifically, using a range of variables, we compared the environmental conditions between:

1. Streams within burned catchments and streams within unburned catchments (across all 10 EMBER catchments).

2. Burned and unburned plots (across all 10 EMBER catchments).

3. B2, B4, B7, B10+ and unburned plots (across all 10 EMBER catchments).

4. B2, B4 and B15+ plots within the Bull Clough study catchment, unburned plots within the Moss Burn study catchment and wildfire plots within the Oakner Clough study catchment.

5. B2, B4, B7 and B15+ plots within the Bull Clough study catchment and unburned plots within the Oakner Clough study catchment.

The subsequent sections provide additional information about the environmental variables used during all five comparisons. This information includes a brief description of each variable, how each variable was sourced and calculated, and tabular results and descriptions of any statistical analysis we carried out.

Comparing streams within burned catchments and streams within unburned catchments

- This experimental set-up relates to Brown et al. (2013) and Holden et al. (2015)

Table S1.2. The source of each catchment environmental variable and how it was calculated. Data was matched to each catchment by using the location information provided in Table 2.1 in Brown, Holden and Palmer (2014).

Response variable	Data source	Data calculations
Monthly temperature (°C)	UKCP09 Met Office 5 km gridded long-term monthly climate observations from 1981 to 2010	Monthly temperature data for each catchment were extracted using ESRI ArcGIS 10.4 and then averaged across the year. Data available from http://catalogue.ceda.ac.uk/uuid/87f43af9d02e42f483351d79b3d6162a
Monthly rainfall (mm)	UKCP09 Met Office 5 km gridded long-term monthly climate observations from 1981 to 2011	Monthly rainfall data for each catchment were extracted using ESRI ArcGIS 10.4 and then averaged across the year. Data available from http://catalogue.ceda.ac.uk/uuid/87f43af9d02e42f483351d79b3d6162a
Elevation (m)	Table 1 in Holden et al. (2015)	The upper and lower elevation values given in Table 1 for each catchment were averaged
Area (km^2)	Table 1 in Holden et al. (2015)	No calculations required as the area values for each catchment are given in Table 1
NVC community	Table 1 in Holden et al. (2015); Table 1 in Noble et al. (2018)	No calculations required as the NVC values for each catchment are given in both tables
Geology	Table 2.1 in Brown, Holden and Palmer (2014)	No calculations required as the underlying geology for each catchment are given in Table 2.1

Table S1.3. Mean (± SEM) monthly temperature, monthly rainfall, elevation and area values for the five burnt and five unburnt EMBER study catchments. *F* test statistics and p-values for the comparisons of monthly temperature and monthly rainfall between burnt and unburnt catchments are from one-way ANOVA tests. Chi-square test statistics and p-values for the comparisons of elevation and area between burnt and unburnt catchments are from Kruskal-Wallis rank sum tests (as the data failed to meet the parametric assumption of homogeneity of variances). Significant results ($P < 0.05$) are highlighted in bold.

Response variable	Burnt	Unburnt	d.f.	*F*	χ^2	*P*
Monthly temperature (°C)	6.38 ± 0.45	5.96 ± 0.58	1,8	0.33		0.584
Monthly rainfall (mm)	106.87 ± 4.96	132.53 ± 6.42	1,8	10.01		**0.013**
Elevation (m)	505.90 ± 27.68	562.70 ± 67.01	1		0.54	0.465
Area (km^2)	1.26 ± 0.20	1.84 ± 0.47	1		0.54	0.462

Comparing burned and unburned EMBER plots

- This experimental set-up relates to Holden et al. (2015).
- Three additional plots (plot 13, 14 and 15) from Great Eggleshope Beck that were bunt during the EMBER study were omitted from the analysis because the methods section in Holden et al. (2015) suggests that they were not used (*e.g.* "*At all 10 catchments,12 soil plots were selected*").

Table S1.4. The source of each plot environmental variable and how it was calculated. Data was matched to each plot using location information provided in a Microsoft Excel spreadsheet by one of the EMBER authors (J. Holden, pers. comm., September 28, 2018).

Response variable	Source	Data calculations
Elevation (m)	Ordnance Survey Terrain 50 digital elevation model	Elevation data for each plot were extracted using ESRI ArcGIS 10.4. Data available from https://www.ordnancesurvey.co.uk/opendatadownload/products.html
Slope (^{o})	Ordnance Survey Terrain 50 digital elevation model	Slope data for each plot were extracted using ESRI ArcGIS 10.4. Data available from https://www.ordnancesurvey.co.uk/opendatadownload/products.html
Aspect (^{o})	Ordnance Survey Terrain 50 digital elevation model	The aspect of each plot was extracted using ESRI ArcGIS 10.4. The aspect of each plot was refined to northerly (N, NE, NW), southerly (S, SE, SW), easterly (E) and westerly (W) aspect categories. Data available from https://www.ordnancesurvey.co.uk/opendatadownload/products.html

Table S1.5. Mean (± SEM) elevation and slope values for the burnt (*n* = 60) and unburnt (*n* = 60) EMBER study plots. Chi-square test statistics and p-values are from Kruskal-Wallis rank sum tests (as the data failed to meet the parametric assumption of normality). Significant results (P < 0.05) are highlighted in bold. **Data were analysed at the plot rather than site level to match the analysis of Holden et al., 2015 (N.B. This could be considered as pseudoreplication, but we wanted to match the analysis of Holden et al., 2015).**

Response variable	Burnt	Unburnt	d.f.	χ^2	*P*

Elevation (m)	485.47 ± 8.03	518.37 ± 12.96	1	7.37	**0.007**
Slope (°)	5.93 ± 0.25	6.88 ± 0.42	1	4.72	**0.030**

Comparing the B2, B4, B7, B10+ and unburned EMBER plots

- This experimental set-up relates to Holden et al. (2015).

- The data sources for elevation and slope values are the same as those listed in Table S1.4 above. However, in this analysis, they are averaged across burning age treatments.

- Three additional plots (plot 13, 14 and 15) from Great Eggleshope Beck that were bunt during the EMBER study were omitted from analysis because the methods section in Holden et al. (2015) suggests that they were not used (*e.g.* "*At all 10 catchments,12 soil plots were selected*").

Table S1.6. Mean (± SEM) elevation and slope values for the "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) EMBER study plots. Chi-square test statistics and p-values are from Kruskal-Wallis rank sum tests (the data failed to meet the parametric assumption of normality). **Data were analysed at the plot rather than site level to match the analysis of Holden et al., 2015 (N.B. This could be considered as pseudoreplication, but we wanted to match the analysis of Holden et al., 2015).**

Response variable	B2	B4	B7	B10+	U	d.f.	χ^2	P
Elevation (m)	486.55 ± 16.83	487.04 ± 15.71	483.02 ± 16.33	485.25 ± 17.05	518.37 ± 12.96	4	7.59	0.108
Slope (°)	5.35 ± 0.47	5.69 ± 0.41	6.12 ± 0.57	6.58 ± 0.53	6.88 ± 0.42	4	8.03	0.090

Comparing the B2, B4 and B15+ plots within the Bull Clough study catchment with unburnt plots within the Moss Burn study catchment and wildfire plots within the Oakner Clough study catchment.

- This experimental set-up relates to Holden et al. (2014).

- The data sources for elevation and slope values are the same as those listed in Table S1.4 above.

- The original spreadsheet sent by one of the EMBER authors did not state which three plots were used at the Moss Burn (unburnt) and Oakner Clough (wildfire) catchments (J. Holden, pers. comm., September 28, 2018). Therefore, we included every plot from both sites within our analyses.

Comparing the B2, B4, B7 and B15+ plots within the Bull Clough study catchment with unburned plots within the Oakner Clough study catchment.

- This experimental set-up relates to Brown et al. (2015) and Holden et al. (2015).

- The data sources for elevation and slope values are the same as those listed in Table S1.4 above.

REFERENCES

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.* University of Leeds, 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.

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.

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.

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.

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.