A review of recent evidence on the environmental impacts of grouse moor management

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Introduction

In support of its charitable purposes, the RSPB has a long-standing interest in halting the illegal killing of protected wildlife on land managed for driven grouse shooting (largely in Scotland and England). In recent years, in recognition of the increasingly urgent need for land use and management to respond to global climate and biodiversity crises, this concern has extended to reducing other detrimental, environmental impacts of grouse moor management. In 2013, RSPB Council approved a paper setting out the need for the statutory regulation of grouse moor management and shooting practice, alongside a desire to identify and work with progressive elements of the grouse shooting industry towards more sustainable grouse moor management practice[1]. In 2016, we published a Viewpoint article reviewing the evidence base on environmental impacts of high-output driven grouse shooting, focusing on the main management practices undertaken on driven grouse moors (i.e. predator control, managed burning of upland vegetation and the treatment of grouse disease) and identifying key knowledge gaps (Thompson *et al*. 2016). We showed that whilst grouse shooting in some forms can have some environmental benefits, there is growing evidence of negative environmental impacts and societal costs associated with the increasingly intensive and sometimes illegal management undertaken on driven moors to achieve large grouse bags. For example, such management damages priority habitats (e.g. blanket bog, Northern Atlantic wet heaths, Alpine and Boreal heaths[2]) and the ecosystem services they provide (e.g. peat/carbon conservation and water quality and flows)[3] and constrains numbers and distributions of priority species (e.g. hen harrier and golden eagle). Such concerns are not new. In a general treatise on game management practices, Aldo Leopold (1933) suggested that "*the recreational value of a head of game is inverse to the artificiality of its origin and hence to the intensiveness of the system of game management which produced it*", whilst specifically in relation to red grouse management Vesey-Fitzgerald (1946) noted that "*The great trouble remains grouse disease, and the root of that trouble lies in the fact that the moors are continually forced to carry stocks far in excess of their capabilities*."

Our call for driven grouse shooting to be regulated via the introduction of statutory licensing sits in the context of increasingly vocal calls from some parts of the conservation and animal welfare sectors for driven grouse shooting to be banned (Avery 2015, Tingay and Wightman 2018). In October 2019, the RSPB announced it was to review its position on gamebird shooting and associated land management.

Here we update our 2016 assessment of the evidence on the impacts of grouse moor management practices as a contribution to that review. Specifically, we first provide brief context on recent changes to the economics and culture of grouse moor management, and then update the evidence assessment in three main categories as follows:

(i) the impacts of burning and other vegetation management;

(ii) the impacts of management of predation and predators;

(iii) the impacts of the management of grouse disease;

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[1] Policy on management practices associated with grouse shooting in the uplands and the need for more sustainable approaches. Council 4/12/87

[2] With the UK's recently published Article 17 report on implementation of the Habitats Directive noting that each of these habitats had an overall assessment of unfavourable/bad

[3] Tackling the conflict in our hills – The RSPB's vision for the UK's mountains, moors, hills and valleys. Board/Council 4/17/90

Finally, we consider the role that grouse moor management might play, in the context of upland land use systems more generally, in making a sustainable contribution to meeting the challenges posed by the climate and biodiversity crises.

Executive Summary

Culture and economics of grouse moor management

- The number of grouse shot in the UK increased by 62% between 2004 and 2016, with consistently high bags from 2009-2018;
- These consistently high bags have been underpinned by increasingly intensive management, especially burning, predator control and the treatment of grouse disease;
- This desire to achieve big bags causes the conflict with birds of prey conservation;
- Whilst driven moors typically generate much higher income from shooting (than walked-up moors), the high management costs mean that many driven moors operate at a loss so that walked-up and driven shoots are reliant on private investment to cover running costs;
- Despite operating losses, the capital (sporting) value attributed to a brace of grouse mean that the value of a moor can be substantially increased (over time) by increasing the average bag size, with running costs recouped at the point of sale of the moor.

Burning (including wildfire) and other vegetation management

- There is a large (and growing) evidence base on the effects of managed burning on upland peatlands - the science is complex with key findings sometimes contested;
- Overall, Glaves *et al*. (2013) found evidence of negative impacts of burning on peatland flora and fauna (8 of 12 studies) and carbon and water (10 of 11 studies), and Brown & Holden (in press) confirm that prescribed burning is associated with increased exposure of the peat surface, elevated erosion risk, lowered water tables and increased overland flow;
- Neither a recent, large-scale experimental study (Heinemeyer *et al*. 2020) nor recent global reviews of management of peatland vegetation (Taylor *et al*. (2018, 2019) concluded that prescribed burning should be used as a routine management tool to conserve or restore peatland vegetation;
- Heinemeyer *et al*. (2020) concluded cutting was marginally more beneficial than burning with non-intervention often the best means of restoring blanket bog function;
- Most studies of the environmental impact of burning peatland vegetation on carbon fluxes and stores are limited by only considering change in the surface peat layers;
- One study found a positive relationship between burning and red grouse numbers, with the post-breeding density of grouse positively correlated with the extent of burning, but there is no consistent evidence of population-level impacts of burning on other species;
- Wildfire is an increasing concern in the UK uplands; most occur in spring and summer, and prescribed fires, including those on grouse moors, are an important source;
- Dry, dwarf shrub dominated peatlands, are particularly vulnerable to fire, with peat ignition and combustion resulting in loss of stored carbon, but further evidence is required to determine if managed burning (to reduce fuel load) or peatland re-wetting (restoration of higher water tables and peat-forming vegetation) is the most appropriate means of mitigating wildfire risk, and the severity of impact;

Predation and predator control

- Satellite tracking technology has revealed that excess, premature deaths of golden eagles and hen harriers are strongly spatially associated with driven grouse moors;
- For golden eagles, the detected increase in mortality halved the survival rate in their first three years of life from 88% (in the absence of human killing) to 44%, and for hen harriers, first-year survival was reduced from 36-54% to 17%;
- The illegal killing of both species continues to limit their breeding populations and ranges, with recent national surveys finding declines and low levels of territory occupancy associated with grouse moor areas. The results of the most recent hen harrier national survey found the population had declined by 24% since 2004 (13% since 2010), but with much more severe declines (57%) on grouse moors - as reflected in a decline in north east Scotland from 28 pairs in the 1990s to just one in 2014;
- A long-term study in the Peak District found that populations of peregrines and goshawks increased in the White Peak (with higher nest occupancy and nest success) but declined severely in the Dark Peak (where grouse moor management is more dominant land use), with confirmed incidents of raptor persecution strongly spatially associated with areas managed as grouse moors;
- In contrast, as found in the Langholm Moor Demonstration Project, in the absence of illegal killing, grouse moor management can be beneficial for ground-nesting birds, including hen harrier, curlew, golden plover and snipe, although the gamekeeping intensity required to achieve these benefits may be considerably lower than levels on modern grouse moors.

Disease management

- Habitat management on grouse moors remains highly favourable for mountain hares, but there is good evidence that culling of mountain hares for louping-ill control (despite a lack of evidence of the efficacy of this practice) may have driven recent, severe declines of mountain hare populations on grouse moors;
- There is further evidence from laboratory studies that the anthelmintics used to treat grouse could pose a risk to the integrity of aquatic ecosystems, and growing concern that reliance of grouse moors on this medication could drive evolution of resistance to the prescribed drugs;
- There is new evidence that the novel red grouse disease, respiratory cryptosporidiosis ('bulgy eye'), associated with grouse moors, is likely to be spread by grit-feeding trays;
- The demographic impact of the disease is considerable – the survival rates of infected adult grouse (over 6 months) declined from 70% to 44% in females and 22% in males, and breeding productivity was reduced by 43% in pairs with a diseased female, attributed to the reduced survival rates of chicks in the first two months of life, as they too become infected;
- These effects of 'bulgy-eye' were estimated to reduce shootable surpluses by 6% on affected moors with a net cost of £0.9 million (2013-2015) across managed grouse moors.

Grouse moor management in the 21st Century

- The UK and devolved Governments have committed to achieving net-zero greenhouse gas emissions by 2050[4] - the Committee for Climate Change has called for woodland cover to increase from 13% to 17% and for peatlands to be restored and vegetation burning to end;
- The evidence suggests that the widespread and growing environmental impacts of grouse moor management as currently practised are not compatible with these objectives, with poor environmental performance driving calls for change;
- However, change may be possible. The Langholm Moor Demonstration Project (2007-2018) succeeded in: (i) restoring grouse populations to the level at which shooting of smaller bags would have been sustainable (ii) initiating the recovery of heather extent for the first time in over 60 years, (iii) halting and reversing the historical declines of curlew, golden plover and snipe against a backdrop of continuing declines in the wider landscape, and (iv) maintaining breeding hen harrier populations at qualifying levels for the Special Protection Area, whilst rendering their predatory impact on red grouse negligible via diversionary feeding;
- Those who manage land for grouse shooting must now decide what role they intend to play in tackling the climate and nature emergencies. Those who embrace change have an important role to play in restoring the natural capital of the uplands thus benefitting from future payments that support the delivery of public goods;
- Those who continue with little regard for the natural capital of the uplands must be held to account for their actions - as noted by Helm (2019) "*responsibility for the consequences of grouse moor management lies with the owners. They are the 'polluters' imposing costs on the rest of us, and they should pay. A more prosperous uplands would start with the licensing of game shoots and then a levy to put right the damage caused. The result would be a more sustainable and, therefore, ultimately more prosperous game industry*."

[4] The Scottish Government ***has set a target of achieving net-zero*** emissions of all greenhouse gases by 2045; Welsh Government aim to cut carbon emissions by 95% by 2050

Methods

In this review, we consider the findings of recent peer-reviewed publications and published reports on the environmental impact of grouse moor management practices, largely published since 2015. The RSPB last reviewed the evidence on the environmental impact of grouse moor management practices in 2012[5] and published a Viewpoint paper on the impact of grouse moor management practices in early 2016 (Thompson *et al*. 2016).

In reviewing the evidence on burning, we have drawn on other reviews and major studies, especially the Natural England evidence review on the effects of managed burning on upland peatland biodiversity, carbon and water (Glaves *et al*. 2013), peer-reviewed papers from the NERC-funded EMBER[6] study and the final report from the Defra-funded project (BD5104) (Heinemeyer *et al*. 2020).

The RSPB has a long-standing interest and knowledge base on the impact of predator control in the uplands. In this review, we draw heavily on earlier work on the illegal killing of birds of prey (e.g. see RSPB 2015[7], 2018[8]) and recent analyses of the fate of satellite tagged golden eagles (Whitfield & Fielding 2017) and hen harriers (Murgatroyd *et al*. 2019) and a wider review on predation (Roos et al. 2018). A comprehensive review of the evidence of the effects of the killing of birds of prey on grouse moors was published in 2020 (Newton 2020).

Additional reference materials were identified from papers and reports held by the authors (and colleagues) and further supplemented by a Web of Science search[9] (all years) for additional sources. The initial Web of Science search identified a total of 228 references, many of which pre-dated our search cut-off date of 2015 or later. Papers from 2015 and later were screened against sources already held, with new papers read and relevant findings incorporated into our review of recent evidence.

[5] Grant, M.C., Mallord, J., Stephen, L. & Thompson, P.S. 2012. The costs and benefits of grouse moor management to biodiversity and aspects of the wider environment: a review. RSPB Research Report 43. RSPB. Sandy

[6] Brown et al. 2014. Effects of moorland Burning on the Ecohydrology of River Basins. Key Findings from the EMBER Project. University of Leeds

[7] RSPB. 2015. The Illegal Killing of Birds of Prey in Scotland 1994-2014: A Review

[8] RSPB. 2018. The Illegal Killing of Birds of Prey in Scotland 2015-17.

[9] Word search terms - ("grouse moor*" OR "grouse management" OR "driven shooting" OR "driven grouse") AND (disease* OR predat* OR raptor* OR "birds of prey" OR burn* OR fire* OR *fire OR environ* OR carbon OR peat* OR soil* OR water OR biodivers* OR wildlife OR bird* OR wader* OR habitat OR vegetat* OR flora* OR invertebrate* OR mammal* OR fungi OR lichen* OR bryophyte* OR fish*)

Evidence Review 1 - Culture and economics of grouse moor management

Grouse management and shooting are largely funded by private investment (Sotherton *et al*. 2009). Thomson *et al*. (2019) acknowledge that whilst shooting (and related activities) can be important to remote and fragile local economies, the data is limited (often gathered by the industry) with expenditure and income varying significantly between estates. Crucially, there is little evidence on the socio-economic value of alternative land uses and in particular of the externalised costs and benefits of grouse moor management, even though the industry itself claims a range of environmental and societal public goods and services, including carbon capture, flood mitigation, wildfire mitigation and local employment (BASC 2015).

The drive to produce large bags of grouse has been at the heart of conflicts between grouse management and environmental outcomes ever since driven shooting began to be practised in the later 19th century (e.g. Vesey-Fitzgerald 1946), and intensification of practices continues to this day. For example, between 2004 and 2016 the number of grouse shot in the UK rose from 400,000 to 650,000 birds (Aebischer 2019), even though the land area devoted to grouse management has fallen over the long-term (Hudson 1992). Robertson *et al*.'s (2017) analysis of long-term and regional variation in grouse bags notes a positive association between bag sizes and gamekeeper densities in the British uplands, but grouse bags in England have remained consistently high (post breeding density >200 grouse/km^2) since the use of an improved form of medicated grit to treat the nematode worm *Trichostrongylus tenuis* was widely deployed in 2007. Medicated grit is now dispensed routinely and at scale (from grit trays) across all driven grouse moors. The increasingly intensive management associated with driven grouse shooting is supported by the construction of new access tracks. In an assessment of the distribution of tracks in the UK uplands, Clutterbuck *et al*. (2020) found that the highest mean density of tracks was associated with areas of heather-dominated vegetation managed by burning or cutting. In Scotland and Wales, the highest density of surfaced tracks on blanket peat was identified in areas of managed heather.

Since 2010, the post-breeding density of red grouse has ranged in England from 239 grouse km^2 to 370 grouse km^2 (July counts on 25 moors) and 84 to 191 grouse km^2 on a sample of 24 Scottish moors (figures derived from GWCT Annual Reviews, data for 2009-2018). Especially in England, these post-breeding densities now contrast markedly with the density of 60-130 grouse per km^2 (varying with gamekeeper density) required to ensure that driven shooting broke even in the late 1980s and early 1990s (Hudson 1992).

A study commissioned by the Scottish Government (McMorran et al. 2020) of the economic performance of four estates practising largely 'walked-up' grouse shooting[10] and four estates practising largely driven grouse shooting[11] found that in all cases revenue was insufficient to cover costs, by a margin of £11,000 - £104,000 on the walked-up estates and by £6,000 - £169,000 on the driven estates. The case studies show that, in general, grouse moors are loss-making enterprises, largely due to the high level of recurrent and staffing costs associated with grouse production, and such findings are consistent over time, with similar outcomes noted by Waddington (1958), Hudson (1992), Sotherton *et al*. (2009) and the Fraser of Allander Institute (2010). Crucially, however, each brace of grouse also has an impact on the capital value of the estate selling grouse shooting. A study by Knight Frank (2014) found that in this context a brace of grouse may be valued at between £3,750

[10] The walked-up moors ranged from 1,600ha to 12,500ha, with 557 brace shot (53 walked-up days on 3 moors) and 1,379 brace shot on a mixed walked-up/driven moor (9 walked up days and 13 driven days)
[11] The driven moors ranged from 1,900ha to 18,000ha with 4,006 brace shot on 54 driven days and a further 192 brace shot on walked-up days

and £5,500, so that sporting estates can achieve a significant financial return on investment by increasing the average grouse bag (over a 10-year period) prior to selling, with driven grouse moors increasing in value by 49% over a decade.

Key points:

- The number of grouse shot in the UK increased by 62% between 2004 and 2016;
- The drive to achieve a shootable surplus of grouse is underpinned by increasingly intensive management, especially burning, predator control and the treatment of grouse disease;
- This desire to achieve big bags is at the heart of the conflict with birds of prey conservation;
- The consistently high numbers of birds produced between 2009-2018 is attributed to the treatment of grouse disease with medicated grit;
- Whilst driven moors typically generate much higher income from shooting (than walked-up moors), the high management costs mean that many driven moors operate at a loss;
- Walked-up and driven shooting are reliant on private investment to cover running costs;
- Though many moors may run at an operating loss, the capital (sporting) value attributed to a brace of grouse mean that the value of a moor can be substantially increased (over time) by increasing the average bag size, with running costs recouped at the point of sale.

Evidence review 2 - Impact of burning (including wildfire) and other vegetation management

Fire is routinely used to manage vegetation in parts of the UK uplands, particularly in support of grouse shooting. Routine burning as part of grouse moor management on upland bogs and heaths has increased heather cover with peat-forming vegetation replaced by heather in many areas (IUCN UK Peatland Programme, 2020). For example, much of the blanket bog found in the North Pennines of England is *Calluna vulgaris-Eriophorum vaginatum* mire (NVC M19), modified over many years by grazing, burning and atmospheric pollution (Averis *et al*. 2014). As a result, large areas of blanket bog and wet/dry heath (including protected sites) are in poor condition (JNCC 2019), characterised by a low water table, a high cover of dwarf shrubs and low cover of peat-forming mosses. Recent palaeoecological studies of blanket bog in in the north of England have revealed that the current dwarf shrub vegetation is atypical and has only been present for the last 100 to 200 years (Blundell *et al*. 2015, McCarroll *et al*. 2016). Both studies note that *Sphagnum* composition has changed over time, with the recent disappearance of some *Sphagnum* species coincident with evidence of frequent burning over the last 200 years.

Natural England undertook a systematic review of the evidence on the effects of managed burning on upland peatland biodiversity, carbon and water. Whilst evidence gaps remained, they found that 8 of 12 studies showed negative impacts of burning on flora and fauna and 10 of 11 studies showed negative effects on carbon and water (Glaves *et al*. 2013). Harper *et al*. (2018) reviewed the impacts of prescribed fire on ecosystem services in the UK concluding that irresponsible burning in the uplands threatens to reduce carbon storage with wider impacts on water quality, flora and fauna.

Despite growing awareness of the scale of these impacts (e.g. Douglas *et al*. 2015), vegetation is still routinely burnt in the English and Scottish uplands, both by managed burning and wildfire, with recent work confirming that burning has recently intensified in parts of the Scottish uplands (Matthews *et al*. 2018, 2020).

Thompson *et al*. (2016) noted that whilst some birds benefit from burning, others don't, particularly those that nest in deep (old) heather or prefer heather/grass mixes or areas of scrub. Despite regulation, burning on peat soils is routine with blanket bog and wet heath regularly burnt even on protected areas where burning is inconsistent with international responsibilities to maintain and restore blanket bog and other upland peatland habitats. Whilst burning leads to the degradation or loss of peat forming vegetation, the long-term effect of burning on below-ground carbon processes was unclear. In contrast, the impacts of burning on peatland hydrology (the water table is lowered following burning), water flows (burning increases runoff during major storm events) and peatland processes (near surface drying and wetting cycles impact on carbon processes) indicate that burning has significant negative impacts on peatland condition and function. The benefits of restoring peatland hydrology to increase resilience to wildfire were contrasted with calls to reduce the impact of wildfire by using fire to reduce fuel load.

Here we provide a brief synthesis of evidence published since Thompson *et al*. (2016) plus a few older sources which we were not aware of when we published the 2016 article, breaking down the environmental impacts of burning into a series of overlapping categories.

This is a complex, sometimes contentious and fast-moving literature, especially with regard to the impact of burning on peatland vegetation and soils and is by far the biggest challenge in the evidence review[12].

Environmental impacts of burning of peatland on carbon fluxes and stores

Four studies have considered the consequences of different land uses (and management interventions) on the carbon sink function of peatlands by using *near-surface* peat (collected via short cores) to quantify and interpret carbon fluxes.

1. Clay *et al*. (2015) monitored carbon stocks and carbon fluxes on a series of known age burns in the North Pennines, last burnt between 1997 and 2009. Whilst burning on these *Calluna*-dominated peatlands initially resulted in reduced losses of carbon (recent burns were smaller sources of carbon compared with older burns), burning did not lead to peat formation and net storage of carbon. This led the authors to conclude that it would be better to convert *Calluna*-dominated ecosystems (dry) to species that are actively peat forming such as a *Sphagnum*-dominated system (wet).

2. Grau-Andres *et al*. (2019) considered the impact of burning peatland vegetation on a dry heath and a raised bog. Both the unburnt dry heath (-0.33 µmol m^{-2} s^{-1}) and raised bog (-0.38 µmol m^{-2} s^{-1}) were carbon sinks. However, following burning, both dry heath (0.50 µmol m^{-2} s^{-1}) and raised bog (0.16 µmol m^{-2} s^{-1}) shifted from being a net carbon sink to a net carbon source, with the difference in the heathland plots being significant. Burning also increased methane emissions on the raised bog but had no significant effect on dissolved organic carbon content of soil water.

3. Marrs *et al*. (2019) derived estimates of below surface carbon accumulation rates using age-depth profiles using near-surface (short) cores from four managed burn frequency treatments[13]. Whilst the negative impact of burning on carbon accumulation rates increased with burn frequency, carbon was still accumulated in the surface peat even after six sequential burns. Marrs *et al*. (2019) therefore argued that prescribed burning could sustain peat growth and carbon accumulation whilst also helping to mitigate wildfire risk. In response, Baird *et al*. (2019) noted that natural peatlands do not require managed burning because they are waterlogged. Indeed, whilst degraded (dry) bogs are inherently more fire prone, intact (wet) bogs are less so because they have a lower cover of dwarf-shrubs as well as higher water tables (Baird *et al*. 2019).

4. The findings of Marrs *et al*. (2019) contrast with those of Garnett *et al*. (2000) who, working on the same experimental plots, found that after 30 years of burning, significantly less carbon was stored in the plots which had been burnt every 10 years.

In contrast to the above studies, Ward *et al*. (2007) measured the carbon stock in longer (1m) cores on the same plots used by Marrs *et al*. (2019) and Garnett *et al*. (2000). Sampling unburnt and burnt plots (9 years into a 10-year burning cycle), they found that burning and grazing reduced carbon stocks in vegetation by 56% and 22% respectively and that burning reduced carbon stocks in the near-surface peat by 60%. However, they did not detect any reduction in carbon stored the older deeper peat. Overall, burning every 10 years led to a loss of 167 g carbon m^{-2} from the peat surface and 88 g carbon m^{-2} from the above-ground vegetation. Assuming losses of this size after each 10-

[12] For example, see Marrs *et al*. (2018) and response by Baird *et al*. (2019) and reply from Marrs *et al*. (2019) and Heinemeyer *et al*. (2018) and response by Evans *et al*. (2019) and reply from Heinemeyer *et al*. (2019).
[13] Reference plots – unburnt since 1923; plot unburnt since 1954; plot burnt every 10 years (burnt six times since 1954); plot burnt every 20 years (burnt three times since 1954)

year burning event, Ward *et al*. (2007) estimate the total loss of carbon to be 25.5 g carbon m^{-2} y^{-1} compared with 73 g carbon m^{-2} y^{-1} as found by Garnett *et al*. (2001).

Young *et al*. (2019) conclude that carbon accumulation rates obtained from near-surface peat (using short cores) should not be used as the only source of evidence on the on the recent effects of management or climate on the peatland carbon store. Near-surface peat is in the zone in which the water table fluctuates (from the peat surface to depths of 50 cm or more) and in which oxygen is often readily available for decomposition. Peat below this zone is subject to much lower rates of decay, mainly because there is less oxygen available. Consequently, carbon accumulation rates estimated for near-surface peat are many times greater than the long-term rates estimated for the deeper, saturated peat which can be modified by events such as drought or fire many years after it was formed. Short cores cannot reveal what is happening, or what has happened, in such deeper peat and therefore cannot be used to determine if a peatland is currently a C sink or a source.

One study has considered the relative impact of vegetation cover on overall carbon fluxes in routinely burned moors, dominated by heather cover. In the South Pennines and Peak District, Dixon *et al*. (2015) found that whilst areas dominated by younger (faster-growing) *Calluna* were a carbon sink, areas dominated by older (slower-growing) heather were a carbon source. On blanket peat, there was no canopy height at which heather-dominated vegetation cover would be a net annual sink of CO_2 prompting the authors to recommend management to reduce heather dominance.

Hydrological impacts of peatland burning

The findings of the NERC-funded EMBER[14] project (Effects of Moorland Burning on the Ecohydrology of River basins) were published in a suite of peer-review papers. Overall, the study found that burning lowered water tables (taking 7-10 years for the water table to return to pre-burn levels), dried the peat and caused loss of peatland vegetation (especially peat-forming mosses), leading to an increase in water run-off, particularly during major storm events (Brown *et al*. 2013, Holden *et al*. 2015). Burning impacted on the near-surface hydrological functioning of peatlands. The removal of surface vegetation, notably the peat-forming mosses which slow the flow of water over the bog surface, and lowering of the water table then caused greater soil surface temperature extremes with associated consequences for biogeochemical, hydrological and carbon processing (e.g. higher temperatures promote more rapid microbial breakdown of peat enhancing production and supply of dissolved organic carbon in stream water). (Holden *et al*. 2014, Brown *et al*. 2015).

Ashby & Heinemeyer (2019) published a methodological critique of the EMBER project. Brown & Holden (in press) responded to the criticisms and undertook a systematic review of the wider literature on impacts of management on peatland ecosystems, finding a consensus on the impacts of burning on for four ecosystem properties:

(1) prescribed burning is associated with increased exposure of the peat surface and/or more erosion

(2) mean and/or maximum soil temperatures at the peat surface increase following prescribed burning,

[14] The EMBER study was conducted in 10 independent catchments – 5 burnt and 5 unburnt; Whereas the unburnt catchments had no recent history of burning (not burnt in at least 30 years) the burnt catchments were regularly burnt; In the burnt catchments, the EMBER team monitored peatland vegetation and wider peatland processes on burns attributed to 4 age categories: <2 years since last burn; approx. 4 years since last burn; approx. 7 years since last burn; >10 years since last burn

(3) prescribed burning alters catchment hydrological functions (e.g. lowering the water table and increasing overland flow) and

(4) prescribed burning reduces aquatic invertebrate diversity (EMBER findings only).

The authors acknowledge that whilst most available studies reported some alteration to soil physical and/or chemical properties and stream chemistry following prescribed burning, the findings from studies on the impacts of burning on *Sphagnum* growth/abundance are much more variable (see next section). The response drew a further response from Ashby & Heinemeyer (2019).

Impacts of peatland burning on vegetation and its roles in ecological succession and peatland function

Milligan *et al*. (2018) published the results of research carried out on the Hard Hill experimental plots (Moorhouse in the North Pennines) established in 1954[15] - reporting on the long-term (60 years) impact of burning and its interaction with grazing on plant communities. They found that some *Sphagnum* mosses and *Eriophorum* sedges (the main peat-forming plant genera in the UK) were more abundant in the most frequently burned treatment (burnt every 10 years) and concluded that burning is not damaging to peat-forming vegetation. The impact of grazing was less clear cut, perhaps because the number of sheep grazing on the moor declined over the duration of the experiment from c.15,400 sheep to c.3,500 sheep in the early 2000s.

Noble *et al*. (2018) monitored the impact of managed burning (and grazing) specifically on *Sphagnum* mosses on the Hard Hill experimental plots (see footnote), including additional data on the presence of *Sphagnum* mosses collected on four reference plots[16]). The *Sphagnum* species recorded responded to the burning treatments similarly. *Sphagnum* abundance and hummock height was greater on the unburnt plots and on the plots burnt every 10 years. However, some species that occurred commonly on the reference plots were wholly missing from the treatment plots (e.g. *S. angustifolium*). Light grazing had no impact on *Sphagnum*-related variables and did not interact with the burning treatments. Plots burnt every 10 years accumulated less vegetation (fuel) than plots subject to the longer 20-year interval between burns leading the authors to suggest that the reduced fuel load in the more frequently burnt plots may have resulted in lower fire temperatures, thus inflicting less heat damage on the *Sphagnum* (Noble *et al*. 2018). In follow-up field and laboratory studies, Noble *et al*. (2019a) monitored fire temperature and the impact of experimental fire on *Sphagnum capillifolium* on the Hard Hill plots. Higher temperatures were recorded in plots with greater dwarf shrub cover (greater fuel load), with higher temperatures associated with a greater proportion of cell damage in *S. capillifolium*. Studies in the laboratory confirmed that higher temperature resulted in a greater amount of cell damage in all five *Sphagnum* species examined (*S. capillifolium*, *S. papillosum*, *S. magellanicum*, *S. austinii*, & *S. angustifolium*). The results show that greater coverage of dwarf shrubs prior to burning produces hotter fires which are potentially more damaging to peatland ecosystems.

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[15] The Hard Hill experiment was established in 1954. Four experimental blocks (each 90m x 60m) were established, with each block comprising six 30m x 30m treatment plots. All plots were burnt at the start of the experiment (1954) after which the plots were subject to one of three treatments – no burning, burnt every 10 years, burnt every 20 years. At the start of the experiment half of the treatment plots were fenced to exclude grazing sheep – so the experiment considered the impact of both burning and burning and grazing combined. See Noble *et al*. (2018).

[16] The reference plots had not been burnt for at least 30 years prior to the start of the experiment in 1954 though may have been burned before that.

Whitehead & Baines (2018) mapped burns (using aerial imagery and from field observation) on a grouse moor in the North Pennines and then constructed a time-series of burn-age categories (a chrono-sequence). Vegetation was sampled in each of five burn age categories[17] across 10 discrete parts of the moor. Heather cover and non-*Sphagnum* mosses increased with time since last burn, with heather cover lower on deeper (wet) peat. In contrast, *Sphagnum* cover was generally greater in the earlier post-burning succession phases, being greatest where peat was deeper (wet). The number of *Sphagnum* species recorded varied with time since last burn, with more species recorded in intermediate burn age categories (3-6, 7-10, 11-17 years) than on the most recent burns (1-2 years since last burn) and in oldest plots (>17 years since last burn). Interestingly, Whitehead & Baines note the presence of peat-forming and more fire tolerant species including *S. capillifolium*, *S. magellanicum* and *S. papillosum*, leading the authors to conclude that peat-forming vegetation benefits from a shorter (more frequent) burn rotation.

Noble *et al*. (2017) monitored the overall impacts of burning, atmospheric pollution and grazing on peat-forming vegetation across 95 blanket bog sites in the north of England. Whilst heather cover was greater and *Sphagnum* cover lower on sites where burning was identified, there was no significant difference in *E. vaginatum* cover between burned and unburned plots. In addition to the impacts of burning, *Sphagnum* cover was negatively associated with livestock presence, leading the authors to conclude that peatlands should not be routinely burned or heavily grazed where the objective is to restore or maintain peat-forming vegetation.

Lastly, we consider a series of experimental studies by Grau-Andres *et al*. (2017a,b,c) who considered the impact of managed fire severity (a measure of the impact of the fire on above and below ground organic matter) on dry heath vegetation (Glen Tanar) and raised bog vegetation (Braehead Moss), including some specific work on *Sphagnum* responses. Specifically, they used rain-out shelters to mimic the effects of drought and removed the moss-litter layer (prior to burning), to assess the effect of the moss and litter layer on fire-induced soil heating. When the moss and litter layer was removed on the dry heath, soil temperature was significantly higher following burning, than when left intact. The authors argued that to keep fire severity low, through the avoidance of burning the protective moss and litter layer, fire managers should burn the vegetation when the underlying moss and litter and soil are moist (Grau-Andres *et al*. 2017a).

In a follow up experiment on the same sites, Grau-Andres *et al*. (2017b) further assessed the relationship between fuel moisture content (moss and litter layer) and severity of fire (impact of fire) following burning. On both sites (following burning), an experimentally drier moss-litter layer resulted in increased consumption (burning) of the moss and litter layer and increased soil heating. The increase in fire severity was much greater on the dry heath (dry) than on the raised bog (wet), where the high-water table kept the surface moss-litter layer moist. Dry heath may be more at risk from drought-induced fires than intact peatlands (Grau-Andres *et al*. 2017b).

Lastly, Grau-Andres *et al*. (2017c) quantified the impact of fire severity on *Sphagnum* mosses on the raised bog site using the experimental approach described above. *S. capillifolium* cover initially decreased with fire severity (5 months after burning) before recovering 22 months after burning, leading the authors to conclude that fire had a limited and short-lived impact on *S. capillifolium*. The authors suggest that this was likely due to negligible *Sphagnum* combustion and lack of extensive heating below the surface, almost certainly due to the water-holding capacity of *Sphagnum* and the high fuel moisture content. The authors suggest that the slightly increased (but not significant)

[17] (1-2 years since burning; 3-6 years since burning; 7-10 years since burning; 11-17 years since burning and burnt at least 17 years ago.

cover of *Sphagnum* after burning may be a result of the removal of the *Calluna* canopy. However, whilst some *Sphagnum* species may be resilient to low-moderate fire severity and achieve rapid post-fire recovery, other species may be sensitive to fire, with regular burning driving changes in species composition (Grau-Andres *et al*. 2017c).

Taylor *et al*. (2018, 2019) reviewed evidence of the effects of management interventions on peatland vegetation (covering a wide range of interventions and including studies from around the world) focusing on the effects of interventions to conserve, restore or create peatland vegetation, including fire. Whilst rewetting was found to be generally beneficial for peatland vegetation, the impact of burning was more variable. The authors further note that findings often vary within and between studies (perhaps due to methodological differences) and that the effects of burning were sometimes not separated from the effects of other interventions. Recognising the wider negative impacts of burning including on animals, peat structure and chemistry, GHG emissions and human health, Taylor *et al*. (2019) conclude that prescribed burning should not be used as a routine management tool to conserve peatland vegetation.

Impact of burning on other animal biodiversity

Thompson *et al*. (2016) noted that burning had complex effects on some bird populations with species such as golden plover and curlew, benefitting, like red grouse, from the open habitat, vegetation structure mosaic and associated predator control, whilst dominant, burned heather cover disfavours species associated with grasslands (e.g. skylark, meadow pipit, woodland and scrub (e.g. black grouse)) and even species requiring deep heather cover for nesting at the highest levels of burning extent and frequency (e.g. merlin, short-eared owl). Amongst other taxa, the EMBER project showed reduction of macro-invertebrate diversity in rivers draining burned catchments (Brown *et al*. 2013).

For birds, these findings were further confirmed by Newey *et al*. (2020) who found that curlew occupancy increased with burn prevalence, whilst golden plover and merlin had peak occupancy at intermediate burn prevalence (41-60% of areas) across the Scottish uplands. Also, at this larger scale, Littlewood *et al*. (2019) surveyed breeding bird numbers in 104 1-km^2 squares across 18 estates in northern England, including 11 managed for grouse shooting (managed at varying levels of intensity) and 7 managed for conservation, livestock grazing and other purposes. The evidence for any additive positive impact of burning was very weak, and only found for golden plover.

Despite the traditional and routine use of burning to boost grouse numbers, there are surprisingly few recent studies on this relationship. However, recently in northern England, Robertson *et al*. (2017b) found that burning extent predicted post-breeding but not pre-breeding red grouse densities on grouse moors. Increasing the proportion of the burned area on moors by 10% increased post-breeding density by approximately 10 grouse km^{-2} with the increased proportion of burning resulting in an increase in the ratio of young to old birds by 0.2. The relationship between the extent of burning and the post breeding density of grouse may explain why the intensity of burning has increased in recent years (Douglas *et al*. 2015, Robertson *et al*. 2017b).

How could heather be managed to support peatland restoration on grouse moors?

Given that grouse moor management is a common land use on upland peatlands with peat-forming vegetation becoming progressively replaced by heather in many areas (IUCN UK Peatland

Programme 2020), some have argued that frequent, 'cool' burning[18] might achieve both the objectives of restoring peat-forming vegetation cover, whilst maintaining some cover of young heather for grouse management purposes: this is the notion of so-called 'restoration burning'[19].

To test this idea, in 2012, Defra commissioned a research project[20] to determine (i) how to reduce the dominance of heather on blanket bog managed for grouse shooting and to support the development of 'active' blanket bog vegetation with a high cover of peat-forming species, particularly *Sphagnum* moss species, and (ii) to test the relative merits of rotational burning and possible alternative management (e.g. cutting) of heather dominated blanket bog in terms of impacts on carbon, water and biodiversity. On each of three study sites in northern England, the costs and benefits of cutting, burning and non-intervention were assessed in terms of their potential contribution to restoring active blanket bog. The findings of the first phase of the project have now been published (Heinemeyer *et al*. 2020). Over multiple categories of response variable (30 measures in total), Heinemeyer *et al*. (2020) concluded that overall, cutting was marginally more beneficial than burning (though more costly to implement) and that non-intervention was often the best means of restoring blanket bog function. The findings of Heinemeyer *et al*. (2020) are published in a large (250 page) report. For brevity, the conclusions are summarised in **Annex 1** alongside results from other relevant studies to provide context.

Relationships between wildfire, managed burning and their environmental impacts

Because peatlands have tended to dry out as a result of climate change and management (Swindles *et al*. 2019), with resultant vegetation change towards dominance of dwarf-shrubs, the question of wildfire risk and its mitigation in these ecosystems is of increasing policy concern, especially as the incidence of wildfire across the UK is considered likely to increase in response to climate change (Granath *et al*. 2016, Harper *et al*. 2018, POSTNOTE 2019). Where the water table is low, the dry peat is vulnerable to more frequent and damaging fires with peat combustion resulting in the loss of stored carbon into the atmosphere (Turetsky *et al*. 2014), and long-term consequences for post-fire recovery of peat-forming vegetation. For example, Lukenbach *et al*. (2016) found that severe burning resulted in drier post-surface soil conditions than low severity fires, and that hummock-forming *Sphagnum fuscum* recovered within three years of a low- severity fire, but not after severe burns.

In the UK, most upland wildfires occur in the spring and summer (Glaves *et al*. 2020). Whilst 99% of all wildfires are small (less than 1ha in size), 4% of fires accounted for 89% of the total area burned in a study in England (Glaves *et al*. 2020). Importantly, ignition for 24% (10 of 41) of wildfires in the Peak District and 36% (8 of 22) of wildfires in the West Pennines began as managed burns, and additional data held by Natural England (cited in Glaves *et al*. 2020) identified managed burning as the source of ignition of 68% (42 of 62) of upland fires, whilst in Scotland, an estimated 60% of wildfires started as managed burns (Luxmoore 2018). It is clear therefore that managed burns,

[18] The Heather and Grass Burning Code (Defra 2007) recommends "quick, cool burns" with the "aim to remove the dwarf shrub canopy but leave behind a proportion of stick and try not to damage the moss or litter layer or expose the bare soil surface."

[19] See - Burning as a tool for the restoration of upland blanket bog: Position Statement by Natural England - http://publications.naturalengland.org.uk/publication/6647144950005760

[20] Defra project (BD5104) Restoration of heather-dominated blanket bog vegetation for biodiversity, carbon storage, greenhouse gas emissions and water regulation: comparing burning to alternative mowing and uncut management

many of which take place on grouse moors, are an important, possibly dominant source of wildfires. However, land managers often argue that managed burning of above-ground vegetation reduces fuel load and can help to protect against the impact of future wildfires by minimising fire likelihood and reducing burn severity (e.g. Santana *et al*. 2016, Harper *et al*. 2018).

The question on which an improved evidence base is urgently needed (Harper *et al*. 2018) is whether managed burning or the restoration of higher water tables and peat-forming vegetation cover is the most appropriate means of mitigating wildfire risk, and the severity of its impacts wherever deeper peat soils offer the latter option. Granath *et al*. (2016) conclude that peatland rewetting reduces the risk of peat combustion and deep burns, especially where it leads to the establishment of a new peat moss layer and the peat moisture content is elevated.

Large wildfires are also a concern to human health, particularly where they occur close to major conurbations. In June 2018, two major wildfires burned over 3 weeks on a mix of degraded heath and bog (some managed as grouse moor) on Saddleworth Moor and Winter Hill (northwest England). These fires emitted smoke and pollutants, yielding a substantial degradation in air quality over Manchester and Liverpool (Graham *et al*. 2020a) with a quarter of the population exposed to high levels of particulates for at least 24 hours with associated short-term health impacts (Graham *et al*. 2020b). Over a 7-day period, 28 deaths were brought forward with a mean daily excess mortality of 3.5 deaths/day (Graham *et al*. 2020b).

Key points:

- There is a large (and growing) evidence base on the effects of managed burning on upland peatlands - the science is complex with key findings sometimes contested;
- Overall, Glaves *et al*. (2013) found evidence of negative impacts of burning on peatland flora and fauna (8 of 12 studies) and carbon and water (10 of 11 studies), and Brown & Holden (2020) confirm that prescribed burning is associated with increased exposure of the peat surface and/or more erosion; that prescribed burning alters catchment hydrological functions (e.g. lowering the water table and increasing overland flow);
- In a global review of management of peatland vegetation, Taylor *et al*. (2018, 2019) conclude that prescribed burning should not be used as a routine management tool to conserve peatland vegetation;
- Most studies of the environmental impact of burning peatland vegetation on carbon fluxes and stores are limited by only considering change in the surface peat layers;
- Findings from studies on the impacts of burning on *Sphagnum* growth/abundance are variable, with variable impacts on different species and some evidence that positive responses are associated with early stages of succession after burning (rather than any long-term change to blanket bog vegetation) and with deeper, wetter peat. Fire temperature is higher when the cover of dwarf shrubs is greater (e.g. greater fuel load) and when the moss-litter layer is dry and ignites - higher temperatures cause greater cell damage to *Sphagnum*;
- One study found a positive relationship between burning and red grouse numbers, with the post breeding density of grouse positively correlated with the extent of burning. Other breeding birds differ in their response to burning. One study found no significant relationships between burning intensity and the density of a suite of breeding waders whilst another found that whilst the proportion of 1-km squares with curlew increased with increasing percentage of the square burned, golden plover and merlin increased only up to the mid-range of burning intensity before declining;

- Wildfire is an increasing concern in the UK uplands - whilst most wildfires are less than 1ha, a small number (4%) accounted for almost all the land burned (89%);
- Most upland wildfires in the UK occur in the spring and summer, with fires started as managed burns an important source of wildfires;
- Dry, dwarf shrub dominated peatlands are particularly vulnerable to fire, with peat ignition and combustion resulting in loss of stored carbon. Some land managers argue that managed burning of the above-ground vegetation reduces fuel load and protects against wildfires;
- Further evidence is required to determine if managed burning (to reduce fuel load) or peatland re-wetting (restoration of higher water tables and peat-forming vegetation) is the most appropriate means of mitigating wildfire risk, and the severity of impact.

Evidence review 3 - Predation and predator control

The evidence on the effects of killing birds of prey on grouse moors has recently been comprehensively reviewed (Newton 2020). On driven grouse moors, gamekeepers kill predators of grouse to maximise the shootable surplus. Red foxes, stoats, weasels and carrion and hooded crows are all shot and trapped legally, with beneficial impacts for other ground-nesting birds as well as red grouse, but this killing often extends illegally to other mammals (e.g. pine martens, badgers) and to birds of prey, notably hen harriers, golden eagles, peregrines, goshawks and red kites (Newton 2020). Thompson *et al*. (2016), noted that the evidence base for impacts of illegal killing and disturbance on birds of prey was already strong and included: (i) that illegal use of poisons to kill predators was associated with grouse moors; (ii) that hen harriers were almost absent from driven grouse moors across the UK even though the habitat on these moors could support several hundred pairs; (iii) that illegal killing of golden eagles and red kites in Scotland, mainly in landscapes used for grouse shooting, had prevented populations reaching favourable conservation status, and (iv) that breeding performance of peregrines is severely reduced on grouse moors relative to other habitats.

Since then, the following advances in knowledge have been made:

Golden eagle populations and survival rates in relation to grouse moors

Whitfield & Fielding (2017) analysed the fates of 131 satellite-tagged young golden eagles over the period 2004-2016. While ranging widely during their pre-breeding years, five were killed, ten died naturally and 41 (31%) disappeared (assumed dead) in circumstances where the tag ceased transmitting with no prior indication of malfunction. These disappearances were strongly spatially associated with some (not all) of Scotland's grouse moor areas and locations with previous, independent records of illegal killing of raptors. Collectively they halved the survival rate of eagles in their first three years of life from 88% (in the absence of human killing) to 44% with the observed level of killing, a reduction sufficient to suppress golden eagle densities in the main affected areas in the central and eastern Highlands and slow recovery of the national population from historical persecution. This is reflected in the findings of the 2015 national survey which found that although the UK golden eagle population increased by 15% between 2003 and 2015, areas of the south-central and eastern highlands were associated with low levels of home range occupancy and a high proportion of those territories that were occupied being held by sub-adult birds (Hayhow *et al*. 2017). Collectively, these findings were sufficient to prompt Scottish Government to commission the 'Werritty Review' of grouse moor management practices, which reported in November 2019 (Grouse Moor Management Group 2019).

Hen harrier population trends and survival rates in relation to grouse moors

Between 2007 and 2017, satellite-tracking of 58 fledgling hen harriers found that 42 (72%) disappeared in the following few months either through illegal killing or through sudden disappearance with no evidence of tag malfunction (Murgatroyd *et al*. 2019). First-year survival rate of these birds was only 17% (as compared with 36-54% in other UK studies of hen harriers) with most deaths occurring in the first 20 weeks post-fledging, during which time the birds that died spent twice as much time on grouse moors (30% of fixes) than those that survived (15% of fixes). Tagged hen harriers were also more likely to die or disappear as the proportion of grouse moor fixes in the last week of life increased and were more likely to be located on grouse moors in the last week of life than at other times. Overall, disappearance rates were ten times greater on grouse moors than in other habitats. These levels of illegal killing of hen harriers continue to limit the breeding population both nationally and locally. Wotton *et al*. (2018) found that the UK and Isle of

Man hen harrier population had declined by 24% since 2004 (13% since 2010), but with much more severe declines (57%) on grouse moors, and this was reflected in the decline of breeding hen harrier numbers in north-east Scotland from 28 pairs in the 1990s to just one in 2014, a loss attributed by the authors to persecution on grouse moors in an area which they suggest, based on habitat availability and quality, could support around 100 breeding pairs (Rebecca *et al*. 2016).

In contrast, the Langholm Moor Demonstration Project has shown that where illegal killing of raptors is prevented, grouse moor management can be beneficial for breeding hen harriers. Ludwig *et al*. (2017) compared two periods of grouse management on Langholm Moor (1992-1999 and 2008-2015) with an intervening period without grouse management (2000-2007) and found that although hen harrier breeding densities were inconsistently associated with periods of grouse management, the proportion of nesting attempts fledging chicks increased from 39% to 78-80% during grouse management periods.

Population studies of other raptors

Other relevant studies have examined long-term changes in regional populations of peregrines, goshawks and merlins. In the Peak District National Park, a 20-year study of the breeding populations of peregrines and goshawks compared the norther part of the Park (the 'Dark Peak', where grouse moor management is a more dominant land use) and the southern area of the Park (the 'White Peak', where grouse moot management is much scarcer) (Melling *et al*. 2018). Over the study period, (i) confirmed incidents of raptor persecution were strongly spatially associated with areas managed as grouse moors, (ii) the populations of both peregrines and goshawks increased in the White Peak area of the Park whilst declining severely in the Dark Peak, and (iii) goshawk and peregrine occupancy of nest sites was roughly twice as great in the White Peak than the Dark Peak, and the probability of successfully fledging at least one chick was twice as great for goshawks and three times as great for peregrines in the White Peak than the Dark Peak. More widely across the UK, peregrine populations increased between 2002 and 2014, but the disparity in the fortunes of lowland and upland populations grew, with upland peregrine populations continuing to be limited by illegal killing and disturbance, and constraints on food supply (Wilson *et al*. 2018).

A thirty-year (1984-2014) study of breeding merlins in the Lammermuir Hills of south-east Scotland found a 42% decline in territory occupancy and a 31% decline in the number of nests located (Barker *et al*. 2017, Heavisides *et al*. 2017). Declines in prey availability and availability of suitable nest sites were identified as likely (but not proven) causes of these declines as a result of intensification of burning management of heather moorland. Nonetheless, it is difficult currently to generalise about the impact of grouse moor management on merlin populations. For example, high densities of nesting merlins are found in the North Pennines (Balmer *et al*. 2013), where grouse moor management is intensive and, in the Berwyn area of North Wales, where active moorland management for red grouse ceased in 1992, numbers of breeding merlins have declined from a peak of 14 pairs in 1992 to eight in 2000 and then to only two pairs in 2014 (Sotherton *et al*. 2017). Much may depend on whether targeted burning of deep heather to discourage other ground-nesting birds of prey (e.g. hen harrier or short-eared owl) also removes all suitable nesting cover for merlins.

Beneficial impacts of predator control for breeding waders

Supporting previous studies, the Langholm Moor Demonstration Project (for more detail of which, see later) yielded local populations of curlew, golden plover and snipe which increase, respectively at 10%, 16% and 21% per annum against a backdrop of wider regional declines of all three species over the same period. Similarly, a recent landscape-scale study by Littlewood *et al*. (2019) found a strong positive association between predator control intensity (gamekeepers per $10km^2$) and the abundance of red grouse over a wide range of keeper densities across 104 $1\text{-}km^2$ squares and 18 estates in northern England. However, for the same three species as considered by the Langholm Moor Demonstration Project, golden plover, curlew and snipe, there was little impact of increasing keeper density beyond 0.1 per $10km^2$, ten times less than the density considered typical on modern grouse moors (Ludwig *et al.* 2019).

Key points:

- Advances in the use of satellite tracking technology have added substantially to the evidence that excess, premature deaths of golden eagles and hen harriers are strongly spatially associated with driven grouse moors;
- For golden eagles, the detected increase in mortality halved the survival rate in their first three years of life from 88% (in the absence of human killing) to 44%, and for hen harriers, first-year survival was reduced from 36-54% to 17%;
- The illegal killing of both species continues to limit their breeding populations and ranges, with recent national surveys finding declines and low levels of territory occupancy associated with grouse moor areas. The results of the most recent national survey found the population had declined by 24% since 2004 (13% since 2010), but with much more severe declines (57%) on grouse moors - as reflected in a decline in north east Scotland from 28 pairs in the 1990s to just one in 2014;
- A long-term study in the Peak District found that populations of peregrines and goshawks increased in the White Peak (with higher nest occupancy and nest success) but declined severely in the Dark Peak (where grouse moor management is more dominant land use, with confirmed incidents of raptor persecution strongly spatially associated with areas managed as grouse moors;
- In contrast, as found in the Langholm Moor Demonstration Project, in the absence of illegal killing, grouse moor management can be beneficial for ground-nesting birds, including hen harrier, curlew, golden plover and snipe, although the gamekeeping intensity required to achieve these benefits may be considerably lower than levels that are typical on modern grouse moors.

Evidence review 4 - Disease management

On driven grouse moors, Red Grouse are treated with a benzimidazole anthelminthic (usually flubendazole) via medicated grit administered at high density (grit boxes 100-200m apart) to limit proven impacts (Newborn & Foster 2002, Redpath *et al*. 2006) of strongyle worm *Trichostrongylus tenuis* infections on breeding success and survival. In addition, sheep may be treated with acaricides, and red deer and mountain hares are shot, in a bid to reduce transmission of the encephalitic viral disease, louping-ill, to red grouse. However, there is no evidence that culling mountain hares is effective in increasing grouse densities (Harrison *et al*. 2010). Thompson *et al*. (2016) noted that the wider environmental impacts of these veterinary treatments were unknown in the field (though one laboratory study of the aquatic toxicity of benzimidazoles had suggested good reason to be concerned), and that the impacts of culling on mountain hare populations were also unknown.

Since the review by Thompson *et al*. (2016), the following advances in knowledge have been made:

Mountain hare culling

An exceptionally long-term study of spring mountain hare densities, centred on the Cairngorms, was published in 2018 (Watson & Wilson 2018) and showed severe long-term declines on moorland over seven decades. Population trends were most resilient on grouse moors until around the turn of the 21st century (the time at which culling of mountain hares for louping-ill control became common practice), and thereafter grouse moors experienced the most rapid declines relative to trends on other moorlands or on alpine ground above the limits of grouse moor management. This is strong, if correlative, evidence that the practice of culling mountain hares for (ineffective) control of louping-ill could have caused severe recent population declines of hares on grouse moors, whilst recognising that habitat management on grouse moors remains highly favourable for hares. This evidence of severe declines of mountain hare populations was corroborated by an analysis of trends of mammals counted on Breeding Bird Survey squares (Massimino *et al*. 2018) which found declines in excess of 50% between 1995-1999 and 2011-2015 in all areas of eastern Scotland where there was sufficient data to estimate trends. A shorter-term study by Hesford *et al.* (2019) in broadly the same geographical area also found declines on driven grouse moors between 2000 and 2010, but with evidence of some recovery thereafter. However, the study areas for this latter study were self-selected by and self-monitored by grouse shooting estates, and no evidence is presented as to whether inclusion in the study influenced the management choices made in relation to mountain hares on these study areas.

Anthleminthic treatment of grouse

Since an initial study by Oh *et al*. (2006), there have been two further laboratory based ecotoxicological studies of the benzimidazole anthleminthics, flubendazole and fenbendazole (Bundschuh *et al*. 2015; Wagil *et al*. 2015a), and all of these suggest the at the acute toxicity of these compounds to test organisms such as *Daphnia* is sufficient to warrant concern over the potential risk to the integrity of aquatic ecosystems, even though there little evidence to date that they occur at observed field concentrations sufficient to be causing serious impacts (Wagil *et al*. 2015b). Nonetheless, it remains the case that there has been no formal field study of the environmental impacts of benzimidazole anthelminthics on aquatic systems whether of agricultural or grouse moor origin, or both.

Recognising that anthleminthics are often prescribed by veterinarians for use on grouse moors without knowledge of local parasite loads, and the potential risk for evolution of drug resistance in *T.*

tenuis populations, Baines *et al*. (2019) have recently experimentally assessed the effects of withdrawing medication across eight grouse moors. Rapid increases in *T. tenuis* egg counts occurred on three of four moors on wet, blanket-peat, but not on four drier, eastern moors, although there was a subsequent 16% reduction in grouse breeding success on these moors. The authors suggest that there may therefore be an inevitable trade-off between parasite monitoring and accordingly targeted use of anthelminthics to help prevent evolution of drug resistance on the one hand, and some grouse productivity penalty on the other.

Acaricide use

There have been no further published studies of the environmental impacts of acaricide treatments, although a comprehensive review of the hosts, transmission and ecological consequences of control of louping-ill virus by Gilbert (2015) found no evidence of the effectiveness of acaricide treatment or lethal control of any of the main transmission hosts (sheep, red deer and mountain hares) in reducing louping-ill infection rates of red grouse to the extent that there are detectable beneficial effects on grouse density.

Emerging diseases and association with intensive grouse moor management practices

Thompson *et al*. (2016) noted the emergence since 2010 of respiratory cryptosporidiosis ('bulgy eye') in red grouse in northern England, evidence of its possible infection of black grouse, and hypotheses that the emergence and spread of this protist pathogen may be associated with high grouse population densities, cross-infection at grit feeding stations and the long-distance 'driving' of grouse during shoots. Since then, Baines *et al*. (2017a) have provided quantitative evidence that grit-feeding trays used by infected grouse are around 2.5 times more likely to be infected with *Cryptosporidium* oocysts than trays not used by infected grouse. Secondly, Baines *et al*. (2017b) have shown clear-cut demographic effects of infection on red grouse; specifically, infection reduced six-month survival rates of adult grouse from 70% to 44% in females and 22% in males, and breeding productivity was reduced by 43% in pairs with a diseased female, the reduction being caused by reduced survival rates of chicks in the first two months of life, as they too become infected. These effects were estimated to reduce shootable surpluses by 6% on affected moors with a net cost of £0.9 million (2013-2015) across managed grouse moors. Although these studies provide growing evidence of association of this novel grouse disease with the high-intensity grouse moors of northern England, there has been less evidence of any impact on black grouse in the same geographical area; in a screening study of 239 live birds and five dead birds, Parsons *et al*. (2017) found evidence of cryptosporidial infection in just one of the dead birds.

Key points:

- Habitat management on grouse moors remains highly favourable for hares, but there is good evidence that culling of mountain hares for louping-ill control (despite a lack of evidence of the efficacy of this practice) may have driven recent, severe declines of mountain hare populations on grouse moors;
- There is further evidence from laboratory studies that the anthelmintics used to treat grouse (flubendazole and fenbendazole) could pose a risk to the integrity of aquatic ecosystems, and growing concern that reliance of grouse moors on this medication could drive evolution of resistance to the prescribed drugs;
- There is new evidence that the novel red grouse disease, respiratory cryptosporidiosis ('bulgy eye'), associated with grouse moors, is likely to be spread by grit-feeding trays;

- The demographic impact of the disease is considerable – the survival rates of infected adult grouse (over 6 months) declined from 70% to 44% in females and 22% in males, and breeding productivity was reduced by 43% in pairs with a diseased female, attributed to the reduced survival rates of chicks in the first two months of life, as they too become infected;
- These effects of 'bulgy-eye' were estimated to reduce shootable surpluses by 6% on affected moors with a net cost of £0.9 million (2013-2015) across managed grouse moors.

Evidence review 5 - Grouse moor management in the 21st century

The UK uplands have long been managed for combinations of sport shooting (red deer and red grouse), livestock production and forestry. The changing balance of these has had major ecological, social and economic impacts for over 300 years (McVean & Lockie 1969) and continues to do so. In particular, the emergence of systematic livestock farming (especially sheep farming) and management of the land for hunting (deer stalking and grouse shooting), supported by drainage, predator control and vegetation burning has had a profound impact on the ecology of the uplands with the grouse moors we see today a much modified relic of something which was once a natural vegetation and faunistic unit (Pearsall 1950). In places, the combined impacts of drainage, grazing (sheep and deer), and burning have led to landscape scale ecological degradation with upland areas in the Highlands & Islands of Scotland variously referred to as "*man-made desert*" and "*devastated terrain*" (Fraser Darling 1947, 1955), an "*inherently infertile region devastated by deforestation and repeated burning, and then opened to heavy and uncontrolled sheep grazing*" (McVean & Lockie 1969) and, simply, "*sheepwrecked*" (Monbiot 2013). And yet, despite the long history of extractive management, largely attributable to farming and game management, many upland areas still comprise internationally important habitats and species assemblages (e.g. Thompson *et al*. 1995) albeit in some need of positive conservation action.

In response to the increasingly urgent need to tackle climate change through reducing GHG emissions and sequestering carbon, traditional upland land use is changing. There has been widespread establishment of wind farms, increasing areas of land are managed with nature conservation aims, there is increasing investment in restoration of peatlands and increasing policy incentives for further forestry expansion in the uplands. Despite these green shoots, agricultural support payments continue to bolster largely unprofitable and environmentally damaging farming systems (Clark *et al*. 2019) whilst failing to support High Nature Value Farming systems which are disproportionately associated with the uplands. In contrast, whilst grouse shooting is less reliant on public support payments, it is heavily reliant on private investment which can only be recovered (in part) through driving up bag sizes and shoot income, with the drive to increase grouse bags exerting further pressure on the upland ecosystem. As with CAP headage payments which drove up sheep numbers, especially in the uplands, the drive to increase grouse bags further threatens the upland ecosystem.

The rate of change at the land use system level is only likely to increase, with the UK and devolved Governments committing to achieving net-zero greenhouse gas emissions by 2050[21]. Changes in land use and land management are a necessary response to climate change, both in terms of reducing GHG emissions (safeguarding existing carbon stocks and sequestering carbon) and regulating water quality and flows (Committee for Climate Change (CCC) (2019). This is particularly true of the large areas of unenclosed bog, heath and grass currently managed for driven grouse shooting.

The CCC (2019) note that forestry and peatland restoration have a key role to play in reducing emissions and storing carbon. Over decades, the collective impact of drainage, burning, grazing and industrial atmospheric pollution in upland peatlands, especially in northern England, has been severe, with loss of vegetation cover and peat forming processes, followed by erosion, increased water runoff (and associated downstream flood risk), increased movement of dissolved and particulate carbon into watercourses and reservoirs, and associated increased water treatment costs

[21] The Scottish Government ***has set a target of achieving net-zero*** emissions of all greenhouse gases by 2045; Welsh Government aim to cut carbon emissions by 95% by 2050

(CEH 2019). For example, whilst England's blanket bogs could be a net carbon sink, they currently release an estimated 0.35 Mt CO_2e yr^{-1} with 75% of these emissions attributed to burning (Natural England 2010). Specifically, to achieve the necessary emission reductions in GHG emissions and gains in carbon storage, the CCC suggest that woodland cover must increase from 13% to 17% by 2050 - this would entail planting 30,000 ha of new woodland per annum (Committee for Climate Change 2019). The CCC (2019) and CEH (2019) have called for peatlands to be restored and for practices such as vegetation burning to end. The UK's upland peatlands are mostly in sub-optimal condition. Field *et al*. (2020) note clear climate and biodiversity benefits from the continued protection and improved management of these carbon-rich habitats (e.g. blanket bog).

Some of these changes will challenge existing land uses. For example, where should woodland expansion be focused so that existing carbon-rich habitats such as peatlands are not damaged (Natural Capital Committee 2020)? What are the implications of climate change imperatives for the practice of traditional land uses such as sheep rearing, deer stalking, grouse shooting and drinking water provision whose footprints currently define the character of our uplands? And what are the opportunities and threats to nature conservation and the contribution of the UK uplands to responding to the biodiversity crisis?

In asking these questions of grouse moor management for the 21st Century, we note that in most cases, it is a loss-making enterprise so that although the economics of driven shooting may outperform those of walked-up shooting (Sotherton *et al*. 2009), they do so by reducing net losses rather than enhancing net profits. Instead, it is the 'locked in' culture of driven shooting coupled to the short-term impact of large grouse bags on the capital value of estates (KnightFrank 2014) that drives intensive management practices and their environmental consequences. Breaking the cultural and economic positive feedback cycle in which large bags inflate capital values which in turn incentivise further intensification, *and* properly rewarding the delivery of public goods such as carbon storage, water flow and quality regulation, biodiversity and recreational access are both likely to be key to ensuring that grouse moor management is environmentally, economically and socially sustainable as a long-term component of upland land use.

Initiatives to do this fully do not currently exist, but the recent 10-year Langholm Moor Demonstration (LMDP) took important steps in this direction. From 2007 to 2018, the LMDP aimed to: (i) demonstrate how to resolve conflicts between moorland management for raptors and red grouse, (ii) maintain the hen harrier population as a viable component of the SPA, (iii) extend and improve the heather moorland habitat beyond its state in 2002, and (iv) improve grouse production such that grouse shooting again becomes viable enough to support moorland management. Overall, the aim was for the site to become "a model for modern, sustainable grouse moor management" (www.langholmproject.com). The context was challenging because the project area (Langholm Moor) (i) had suffered long-term loss of heather cover since the late 1940s and was now isolated from other grouse populations (Ludwig *et al.* 2020); (ii) was withdrawn from active grouse management in the mid-1990s (Redpath & Thirgood 1997); (iii) was likely to be experiencing greater predation pressure from establishment of commercial conifer plantations in the wider landscape (Ludwig *et al*. 2018a, 2020); and (v) did not benefit from reductions in sheep grazing intensity until four years into the project (Ludwig *et al*. 2020). Although the grouse shooting target was not met and attempts to achieve it were abandoned before the end of the project, the project nonetheless succeeded in: (i) restoring grouse populations to the level at which shooting of smaller bags would have been sustainable (Ludwig *et al.* 2017), (ii) initiating the recovery of heather extent for the first time in over 60 years (Ludwig *et al.* 2020), (iii) halting and reversing the historical declines of curlew, golden plover and snipe against a backdrop of continuing declines in the wider landscape (Ludwig *et* *al.* 2019), and (iv) maintaining breeding hen harrier populations at qualifying levels for the Special Protection Area (Ludwig *et al*. 2017), whilst rendering their predatory impact on red grouse negligible via diversionary feeding (Ludwig *et al.* 2018b). During this time, agri-environment and SSSI management funding contributed modestly to the costs of livestock reduction and heather restoration management. However, with more comprehensive funding support for public benefits and over a longer timescale with more contiguous heather cover and the likely benefits of that for increase in red grouse carrying capacity and reduction in predation vulnerability Ludwig *et al*. 2018a, 2020), what might be achievable?

Answering this question would require a willingness to shift away from single purpose to multi-purpose land use and management, and would be very different to the current approach on most grouse moors of focusing specifically on managing the habitat (burning), predators (predator control) and grouse (medication) to achieve the high post-breeding density of grouse required for driven shooting. The fact that many individual estates may practise either driven or walked-up grouse shooting at different times of the shooting season or in different years suggests that a shift in approach should be possible, especially if the multiple benefits of legal and sustainable management are better understood, accepted and rewarded.

What does the future hold for the vast areas of land currently managed for driven grouse shooting? There can be little doubt that current levels of intensive and sometime illegal practice fall far short of what is required to restore degraded habitats and recover the populations of species currently kept in check by shooting, poisoning and trapping. These 19th Century practices have no place in 21st Century Britain. Effective regulation is now required to hold those who continually flout the law to account. Anything less will fail to realise the changes required to tackle the climate and nature emergencies.

Those who manage land for grouse shooting must now decide what role they intend to play in tackling the climate and nature emergencies. This is no longer about words – this is about action. As noted by Helm (2019) "*responsibility for the consequences of grouse moor management lies with the owners. They are the 'polluters' imposing costs on the rest of us, and they should pay. A more prosperous uplands would start with the licensing of game shoots and then a levy to put right the damage caused. The result would be a more sustainable and, therefore, ultimately more prosperous game industry*." Those who choose to embrace a different path have an important role to play in restoring the natural capital of the uplands and will be better positioned to benefit from any future payments that support the delivery of public goods.

In line with gamebird hunting practice in other parts of Europe, the introduction of regulation need not mean that grouse shooting is no longer possible. Indeed, enhanced regulation of management and shooting practices would better protect natural resources and improve the environmental and societal credentials of grouse shooting. This of course only holds if the management required to achieve a shootable surplus is in harmony with the delivery of other environmental outcomes.

Conclusions

We have reviewed the primary literature published since 2015 on grouse moor management, including culture and economics, burning and wildfire, predator control, the treatment of grouse disease and the role of grouse shooting in the 21st Century, building on previous activity – Council paper 4/12/87[22], Grant *et al*. 2012, Thompson *et al*. (2016) and Council paper 4/17/90[23].

The restoration of the UK's upland peatlands has a key role to play in tackling the climate and nature emergencies (Field *et al*. 2020). Rather than continuing to burn our peatlands, we need to re-wet them and reintroduce peat-forming *Sphagnum* mosses to increase resilience to wildfire and secure a wider range of peatland ecosystem services. This is consistent with our call for an end to burning on blanket bog in the English uplands, supported by legal action taken by the European Commission and more recent calls for an end to burning peatland habitats in the Scottish uplands (see Annex 2).

The illegal killing of birds of prey continues. We note new evidence linking proven illegal killing and 'sudden disappearance' of satellite-tagged golden eagles and hen harriers with grouse moors.

Despite concerns, medicated grit is routinely used at scale. Grouse numbers have remained consistently high since the introduction of medicated grit in 2007. We note concerns with the emergence of resistance to the prescribed drugs and the transmission of new diseases.

Whilst well-managed uplands may provide a range of ecosystem services, the increasingly intensive management of habitats and species needed to produce the densities of grouse required for driven shooting is often at odds with the conservation of priority habitats (e.g. blanket bog, wet heath), priority species (e.g. golden eagle, hen harrier) and natural resource protection. Though the impact of some management practices (e.g. burning peatland vegetation) are contested and knowledge gaps remain, we remain unconvinced that big-bag driven-grouse shooting will ever be viable without intensive programmes of habitat management, predator control and grouse medication, making the attainment of environmental improvement highly unlikely without a major change in the culture, behaviours and management practices associated with driven shooting.

The negative environmental impacts associated with increasingly intensive and sometime illegal grouse moor management practices have driven calls for driven grouse shooting to be banned, with new movements (e.g. Wild Justice, Revive) and environmental commentators (Macdonald 2019) all calling for driven grouse shooting to be banned both on animal welfare (Anon 2019) and environmental grounds (Armstrong 2019). The growing evidence base increasingly justifies such a view, though we note that the outcomes of the Langholm Moor Demonstration Project show that, set in the context of financial support to deliver a wider range of public benefits from moorland ecosystems, then small-bag, low intensity grouse shooting could have a place. This is consistent with the views of Helm (2019) who notes whilst *"some grouse are, on balance, fine for nature; lots of them are bad".* In the case of grouse shooting, *"there is a considerable environmental difference between some and a lot. In the absence of proper economic incentives and licensing, it is easy to predict that there will be too much*" (Helm 2019).

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[22] Policy on management practices associated with grouse shooting in the uplands and the need for more sustainable approaches. Council 4/12/87

[23] Tackling the crisis in our hills – The RSPB's vision for the UK's mountains, moors, hills and valley. Board/Council 4/17/90

Key Knowledge gaps:

Context - Grouse moor management in the 21st Century

The culture and economic model that collectively drive a desire to achieve ever larger game bags is the key problem;

The capital value of shooting estates is based on game bags, with a brace of red grouse valued from £3,750 to £5,500;

The demand for big bags, supported by intensive management practices (predator killing, vegetation burning and treatment of disease) and supporting infrastructure (e.g. tracks) is detrimental to achieving a suite of environmental outcomes across those upland areas where driven grouse shooting is currently practised;

As noted by Helm[24], whilst 'Some deer, some grouse and some pheasants are, on balance, fine for nature; lots of them are bad';

The environmental and socio-economic costs of driven grouse shooting have not been adequately assessed to date.

Some key questions:

What level of management (gamekeeper density, vegetation management and grouse management (e.g. treatment of disease)) and associated grouse densities are consistent with achieving desirable outcomes for the public (sites/habitats in favourable condition, thriving biodiversity, improved raw water quality, enhanced flood attenuation and increased peat carbon storage)?

What grouse bags and styles of shooting are consistent with management that delivers these environmental outcomes?

Is there demand for licensed (regulated) shoots that offer smaller, environmentally sustainable bags (driven or walked-up) and how can demand be shifted from environmentally unsustainable, 'big bag' shooting?

Further research is required to assess the full socio-economic and environmental costs of driven grouse shooting. In particular this requires quantification of the costs of management interventions associated with driven grouse shooting for which there is evidence of negative impact on the environment and people (e.g. impact of burning on habitat, carbon-rich peat soils, water quality and flows; illegal killing of protected species; impact on access/recreation; use of lead ammunition).

Context - Impact of burning on upland ecosystem services

Fire is widely used to manage upland habitats in Scotland and England, with peatland habitats (blanket bog and wet heath) routinely burnt, even in protected sites, to 'improve' foraging for grouse, livestock and red deer (Scotland);

Burning is frequently cited as a reason why blanket bog and wet heath are in poor condition;

[24] Helm, D. 2019. Green and Prosperous Land – A Blueprint for Rescuing the British Countryside. Collins. London

Despite recent major field studies and evidence reviews, the impact of managed burning on carbon processes (storage, sequestration and cycling) is the subject of an acrimonious debate within the research community;

Much of the burning in the uplands occurs in the upper reaches of major upland catchments in northern England;

Several recent studies have found that water run-off is greater in burnt catchments (than unburnt catchments) during storm events;

Several studies have found a strong positive correlational relationship between burning on peat (new burns) and water colour at a catchment scale; However, these results have been challenged, with a number of studies failing to find a similar relationship (e.g. increased colour) at a plot scale;

The treatment of water colour is a costly process, with treatment costs largely borne by water customers;

A key question:

Given the loss of carbon (as Dissolved Organic Carbon) and associated water treatment costs (paid for by water customers), what is the impact of vegetation management interventions on water colour at a range of scales? This question would be amenable to a field-based experiment (contrasting sub-catchments).

Context: Managing wildfire risk and impact

The incidence of wildfire is rising and is increasingly prevalent in the late spring and early summer months, particularly during periods of prolonged drought;

Whilst some fires undoubtedly start as managed burns, many are started accidentally (and deliberately);

On open habitats, wildfires have the potential to burn across large areas of land, making fire-fighting challenging and with potentially major environmental impacts;

Several researchers and other interested parties have suggested that the best way to reduce the incidence of wildfire is to reduce the fuel load (vegetation cover) across open habitats, particularly in known high fire-risk areas;

Some key questions:

How do we reduce the ignition, spread and impact of accidental/unmanaged fires, particularly fires that start outside the burning season?

To what extent do prescribed fires increase or reduce wildfire risk?

Does controlled managed burning have a role to play in reducing the potential spread and impact of a wildfire?

What contribution can other management interventions (e.g. cutting, peatland restoration) make in reducing the spread and impact of a wildfire?

Context: Predation and predator control

The UK has high densities of mesopredators, with some priority birds (e.g. breeding wader birds) significantly affected by predation;

The attainment of big grouse bags is underpinned both by the legal control of generalist predators and widespread illegal killing of protected wildlife, especially birds of prey;

Though the control of foxes and crows may benefit some priority breeding birds (e.g. breeding waders, black grouse) the RSPB (and others) are keen to move away from routine lethal control of predators and are currently exploring other means of reducing predator numbers and predation;

The combination of the loss of apex predators (nationally and locally), increased food subsidy in the countryside (e.g. released gamebirds, fallen livestock, roadkill) and landscape features which assist the movement of predators through the countryside (e.g. woodland, tracks/roads) may all be contributing to the predation problem;

Some key questions:

What role might a recovering population of golden eagles (in areas where populations are currently suppressed) and an active policy of re-introducing an apex mammalian predator (e.g. Lynx) have on mesopredator numbers and predation on populations of priority birds and grouse?

What is the impact of commercial forestry and forest proximity on predation pressure and predator control requirements for the conservation of ground-nesting birds on open habitats (adjacent to forestry) in the uplands?

Context: Disease management

The treatment of grouse disease via the provision of medicated grit, at a landscape scale, has increased grouse numbers, but the impact of these medications on other species and the wider environment is unknown;

Some key questions:

Field studies on the environmental impact of the use of benzimidazole anthelmintics are required to assess the impacts on aquatic systems (at a range of scales) and on other taxa including invertebrates, other species that ingest the grit (e.g. small passerines, waders, black grouse) and on other routes of transmission (e.g. predation of medicated grouse)

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ANNEX 1. Key results from Heinemeyer *et al*. (2020)

<u>Vegetation effects</u>: Heinemeyer et al. (2020) found soil moisture was significantly higher on cut than burned plots. Cutting encouraged re-establishment of a peat-forming 'typical' bog community, particularly at the wettest site, and caused no lasting peat compaction but did reduce micro-topography at the plot-level. In dry conditions, cut sites had higher peat moisture and water table, with cut vegetation (left on surface) helping to retain soil moisture (as per Grau-Andres et al. 2017b). Burning was the least beneficial form of management intervention in promoting 'active' bog vegetation. Non-intervention had few, if any, downsides apart from limited recovery of a peat-forming bryophyte layer at the driest site.

In a related study comparing three different areas of blanket bog in the Cheviot Hills, North Pennines and Peak District), Noble et al. (2019b) found no evidence that burning was effective as a restoration tool to encourage Sphagnum, or that removing the canopy by burning increased Sphagnum re-introduction success. Whilst dwarf shrub cover increased after burning, remaining high 10+ years later, recently burned plots had more bare peat and a thinner moss layer, probably due to moss being consumed or dried out by fire. Whilst Sphagnum recovered after burning, a high proportion of existing Sphagnum cover was still bleached one year after burning.

In an operational study, the RSPB stopped burning on its Geltsdale reserve in 2009. In an effort to improve the state of the blanket bog and wet heath, sheep were removed, drains were blocked and vegetation cut (Garnett et al. 2019). Between 2005 and 2018, RSPB staff monitored vegetation response on 6 plots that were subsequently burnt and 6 plots that were subsequently cut in 2005. Prior to intervention Sphagnum cover averaged 3.5% on the 'cut' plots and 3.2% on the 'burnt' plots. By 2018, Sphagnum cover had increased to an average of 13% on plots last cut in 2005 and to 4% on plots last burned in 2005. Whilst Sphagnum cover initially fell to zero following burning, it increased to 5% the year after it was cut. By 2018, twice as many Sphagnum species were recorded on the cut plots as on the burned plots. Over the same time period, heather cover increased to 80% on the burned plots and 60% on cut plots. Whilst the mean number of dwarf shrub species recorded was more variable, twice as many species were recorded on the cut plots than burned plots by 2018 (Garnett, unpublished).

<u>Hydrological effects</u>: Heinemeyer et al. (2020) found that whilst cutting resulted in post-management stream water phosphorus concentrations almost three times higher than burning (perhaps due to continued leaching from decomposing cuttings), other stream water quality indicators, including levels of dissolved organic carbon (DOC), varied seasonally and between sites, but did not show any significant impact of management treatment. Contrary to findings from other studies, management did not cause any significant change in either DOC or POC stream export rate.

Though variable, cut plots had a higher water table (2-4 cm) and soil moisture than burned plots with the effects particularly apparent in summer and on plots where cut vegetation remained in-situ. When data on water flows and rainfall were combined, the higher water table on cut plots resulted in reduced catchment stream water loss from the cut catchments compared to the burned catchments at two of the three sites, with cut catchments showing 10% and 20% lower water loss than the burned catchments in the first and second management cycle, respectively. Up-scaled flow volumes indicated potentially significant reductions in downstream peak river flooding (as per Holden et al. 2015), estimated to be up to 50 cm under cutting compared to burning scenarios.

<u>Carbon flux effects</u>: Heinemeyer et al. (2020) used a range of methods to examine the impacts of cutting, burning and non-intervention on soil respiration, Net Ecosystem Exchange[25] (NEE) and Greenhouse gas emissions.

Chamber flux measurements showed little field evidence that management intervention (cut/burn) significantly affected soil respiration fluxes, but NEE (loss of carbon dioxide) was greater (overall) in the uncut than cut or burned plots after management intervention.

There was a measured net efflux (outward flow) of CO_2 on burned (but not cut) plots on two of the three sites. Annual losses of carbon were greater from burned than cut plots in 2013, but four years after management, carbon losses from burned and cut plots, averaged across the three sites, were similar.

The up-scaled annual estimates of NEE showed that both burned and cut plots switched from being a net carbon sink to a net carbon source after management. The pattern for untreated plots was more variable with the wettest site found to be a net carbon sink (over 5-years) whilst the driest site was a small net carbon source.

Measurements of methane flux were highly variable and inconsistent. Whilst there was no significant effect of management intervention (cutting/burning) on methane fluxes from non-vegetated areas, methane fluxes from vegetated areas were higher from uncut plots than from burned plots. Whereas methane flux (highest on the wettest site) was positively correlated with water table depth in the four weeks prior to measurement and with soil temperature and sedge cover, fluxes of N_2O were consistently low (at all 3 sites) and showed no effect of management.

To enable predictions of impacts of the various interventions on carbon flux balance and carbon budgets, the results from the different treatments were scaled up from plot to catchment scale. The scaled-up estimates of Net Ecosystem Carbon Balance (NECB) and net GHG emissions predict that over the five years, the non-intervention (uncut/unburned) areas were either a very small carbon source (average NECB) or a small net carbon sink (median NECB). However, there was considerable variation between sites with one site a carbon source every year and another site a carbon sink in 3 consecutive years. The differences in NECB between sites and years were primarily due to variation in NEE, and to CH_4 fluxes being high in the wet years of 2015 and 2016.

Carbon losses attributed to cutting and burning were (on average) 8 times greater than the gains achieved on the non-intervention (unmanaged) plots. Whilst unmanaged, wet plots showed the greatest carbon gains, the drier unmanaged plots were a small net carbon source. The size of the net carbon source in the burning scenario was higher than that of the cutting scenario, largely because of the direct loss of carbon attributed to the vegetation burning and perhaps because ongoing losses attributable to the breakdown of the cut vegetation were not accounted for.

Overall GHGs, mean net GHG emissions were positive (e.g. a net emission), apart from the uncut management scenario at one site. Mean net GHG emissions under the burned and cut management scenarios were very similar (excluding additional emissions from either burning biomass or the management intervention) and were much greater (on all sites) (45%-559%) than the uncut scenario.

[25] Soil respiration measures production of carbon dioxide from soil microorganisms, plant material etc; Net Ecosystem Exchange is a measure of the net exchange of carbon between the peatland and the atmosphere (per unit ground area) and is a measure of whether the peatland is functioning as a carbon sink or source; The greenhouse gas emissions are a measure of the loss of carbon dioxide, methane and nitrous oxide

Long-term methane flux data highlight the need to gain more evidence in relation to water table and peat moisture thresholds for maintaining a net negative GHG emission balance on generally wetter and/or restored sites.

Finally, Heinemeyer et al. (2020) considered historic fire frequency and peat carbon accumulation. The results from the modelled and up-scaled fluxes used to estimate the NECB suggested that, after accounting for carbon losses from burning the vegetation (but not losses from long-term brash decomposition), the burned plots were a greater net carbon source than cut plots. However, an analysis of the actual peat collected in surface cores from all sites showed that carbon accumulation rates for all sites under burning management were similar to the only previously reported estimate (Garnett et al. 2000) for unburned management (in a burn comparison using similar methods) over the same period.

In order to explore discrepancies in peatland carbon sequestration between flux and stock approaches, and to relate carbon accumulation to past burn frequencies, a peat core study was conducted, with a ***1-metre core*** *taken from single burnt plots in each study area.*

Averaged over all sites, burns were found to have been more frequent, and carbon accumulation rates higher, over the period since 1950 (versus 1700-1950). The site with the greatest Sphagnum cover (least damaged) had the lowest burn frequency in recent history (since 1950) leading Heinemeyer et al. (2020) to surmise that the other sites had been burnt more frequently and subject to more intense (hot) fires. Carbon accumulation rates over the periods 1950-2015 and 1700-1850 were greater on the most frequently burned site which was linked to peat bulk density with the carbon accumulation rates positively related to charcoal abundance (Heinemeyer et al. 2018). This finding was inconsistent with the plot-scale NECB estimates which showed the greatest net carbon losses were from burning compared to either uncut or cut plots (including carbon losses attributed to burning but not accounting for ongoing losses from decomposition of cuttings). Post-burn charcoal was identified as a potentially crucial component in explaining reported differences in burning impacts on peat carbon accumulation, as assessed by carbon fluxes or stocks. (Heinemeyer et al. 2018). The finding that burning on peatlands could be net beneficial for carbon sequestration was challenged: Evans et al. (2019) questioned the experimental design (especially the lack of an unburned control), the choice of and knowledge of past management of the study sites, the selective use of Moorhouse plots (as an unburned reference site[26]) and the use of surface cores (5cm cores taken from peat surface), used (incorrectly – see Young et al. 2019) to draw conclusions on carbon accumulation within the whole peat column. Evans et al. (2020) highlight the discrepancies in findings attributed to the different methods used to measure carbon flux and accumulation, noting that carbon emissions attributable to the actual burning of the vegetation would further exacerbate the discrepancy noted between core and chamber-derived carbon balance estimates.

<u>*Cranefly emergence, abundance and bird population modelling*</u>*: Heinemeyer et al. (2020) examined the impact of cutting/burning on cranefly (tipulid) emergence and abundance. Cut plots were consistently wetter than burned plots, and this resulted in significantly more craneflies emerging in the dry summer of 2014. However, in wetter years (2015 & 2016) the effect was reversed with more craneflies emerging (significantly more in 2016) from burned plots. Cranefly emergence was consistently lower on the wettest site, particularly in the wetter, cut plots. These findings appear to*

[26] Prior to establishing the Hard Hill experimental plots, the proposed experiment area was burnt. Plots were then assigned a treatment (burning/grazing) with burning conducted on short (every 10 years) or long rotations (every 20 years) and either grazed or ungrazed. The reference plots were located outside the Hard Hill experimental area plots and had not been burnt for at least 30 years prior

reflect a lower and upper soil moisture limit for optimum cranefly emergence between 80% and 95%. When cranefly abundance was modelled using transect data, mean abundance was 64% higher on the cut sub-catchments when compared with burnt sub-catchments.

The modelled implications for golden plover fledging production showed that numbers would be higher in cut than burned areas, with the effect strongest in the relatively dry year of 2014 when cranefly abundance was lowest. Modelling of the effects of drier summers (as predicted under climate change), based on the cranefly emergence and soil moisture data, predicted a greater resilience to future drier summers of upland bird numbers (i.e. dunlin, golden plover and red grouse) under cutting, particularly when leaving brash, than under burning. However, the potential that cuttting might make generally wetter sites too wet for cranefly larvae survival (i.e. lower emergence in wet years) and more detailed changes in plant species composition (specifically key ecological species) in response to environmental changes and micro-topographic management impacts on nesting preferences by birds (e.g. importance of hummocks for dunlin) were not included in the model.

Key points

- Heinemeyer *et al*. (2020) examined the costs/benefits of using cutting/burning to restore heather-dominated blanket bog back to a functioning state;
- Over multiple measures (30 in total), Heinemeyer *et al*. (2020) concluded that cutting was marginally more beneficial than burning (though it was more costly) - non-intervention was often the best means of restoring blanket bog function;
- Burning was the least beneficial management intervention in promoting ‘active’ bog vegetation. Noble *et al*. (2019) and Taylor *et al*. (2019) also concluded that prescribed burning should not be used to conserve peatland vegetation;
- The water table and soil moisture were typically higher on cut plots (particularly in the summer and on plots where cuttings left on soil surface) than on burnt plots;
- Combining water flow/rainfall data, the higher water table on cut plots resulted in reduced catchment stream water loss compared to the burnt catchments (two of three sites), with cut catchments showing 10% and 20% lower water loss than burnt catchments in the first and second management cycle, respectively, with potentially significant reductions in downstream peak river flooding (as per Holden *et al*. 2015), estimated to be up to 50 cm under cutting compared to burning scenarios;
- Heinemeyer *et al*. (2020) looked at the impact of cutting/burning on a range of measures of carbon flux with a mix of treatment specific, year specific and plot specific findings;
- Up-scaled annual estimates of Net Ecosystem Exchange found that both burnt and cut plots switched from being a net carbon sink to a net carbon source after management;
- Measurements of methane flux were highly variable and inconsistent;
- Non-treatment plots were either a small carbon source or small carbon sink with considerable variation between sites and years (e.g. wet and dry years);
- Carbon losses attributed to cutting and burning were (on average) 8 times greater than the gains achieved on the non-intervention (unmanaged) plots with more carbon lost overall under the burning than cutting scenario;
- Mean net GHG emissions under the burning/cutting management scenarios were similar – they were all positive and much greater than the non-treatment scenario;

- The results from the modelled and up-scaled fluxes suggested that the burnt plots were a greater net carbon source than cut plots;
- Heinemeyer *et al*. (2020) used 1 metre peat cores to examine long-term fire frequency and carbon accumulation. Averaged over all sites, fires were more frequent, and carbon accumulation rates higher, over the period since 1950 (versus 1700-1950). The site with the greatest *Sphagnum* cover had the lowest burn frequency leading the authors to surmise that the other sites had been burnt more frequently and subject to more intense (hot) fires;
- Over the periods 1950-2015 and 1700-1850 carbon accumulation was greatest on the most frequently burnt site (with carbon accumulation rates positively related to charcoal abundance) (Heinemeyer *et al*. 2018). This finding was at odds with the Net Ecosystem Carbon Balance estimates which showed the greatest net carbon losses were from burning compared to the uncut or cut plots;
- Evans *et al*. (2019) questioned the experimental design, the choice of and knowledge of past management of the study sites, the selective use of Moorhouse plots (as an unburned reference site) and the use of surface cores (5cm cores taken from peat surface) (see also Young *et al*. (2019).

ANNEX 2 – The RSPB and other bodies have called for an end to burning in the uplands of England and Scotland

We have continued to press the European Commission to ask the UK Government to end burning on Northern England's protected blanket bogs (Special Areas of Conservation). In 2016, following submissions by the RSPB, the EC commenced legal action against the UK Government, and escalated it in 2017. With the threat of European court action looming, the UK Government committed to end burning on English blanket bog SACs by June 2019: inviting estates to volunteer not to burn blanket bog while they negotiated with Natural England to give up their legal consents to burn. If an insufficient number of estates refused to give up their legal consents, Defra proposed to amend the Heather & Grass Burning Regulations to end burning on deep peat. In June 2019, the Government accepted that this approach had failed, with Natural England managing to revoke/modify less than half of the consents to burn. It is now evident that some of the estates that volunteered to stop burning continued to burn. Whilst Defra Ministers have repeatedly stated that burning will end, most recently in response to the Committee on Climate Change calls for burning to end, no legislation has been forthcoming. In response to Government inaction, we have escalated our call (in coalition with other eNGOs) calling on Defra Ministers to ban burning in the uplands, to publish the long-overdue strategy for England's peatlands and to set out how we restore our peatlands to good health. Likewise, in response to the climate and nature emergencies, Scottish Environment Link has written to the Scottish Government calling for an end to burning on peatlands, highlighting the key role that healthy peatlands play in protecting vital carbon stocks and reducing carbon emissions.