

Socio-economic and biodiversity impacts of driven grouse moors in Scotland.

Part 2. Biodiversity impacts of driven grouse moors in Scotland



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1 Background

1.1 Policy context

In May 2017, the Cabinet Secretary for Environment, Climate Change and Land Reform announced commissioning of “*research into the costs and benefits of large shooting estates to Scotland’s economy and biodiversity*”¹. A related Programme for Government (2017-2018) commitment published in September 2017 states that a research project will be commissioned to “*examine the impact of large shooting estates on Scotland’s economy and biodiversity.*”

The focus of the Cabinet Secretary’s announcement concerns ‘driven grouse shooting’ estates.

1.2 Objective of the research

The main objective of the overall research project – of which this review on biodiversity impacts is a component - is to consider the socio-economic and biodiversity impacts of driven grouse moors in Scotland. Previous research in this field has already estimated the actual (direct and indirect) economic contributions of shooting estates in Scotland whilst also providing evidence for the wider social and environmental impacts (Hindle et al. 2014; PACEC, 2014; Mc Morran et al. 2015; Wightman & Tingay 2015;). There is also other pre-existing research that can help understand the environmental and biodiversity impacts of the activities which take place on grouse moors (Grant et al. 2012; Mustin et al. 2012).

From July to October 2018 analysis was undertaken by James Hutton Institute and Scotland’s Rural College (SRUC) on the socio-economic and biodiversity impacts of driven grouse moors in Scotland. This report is one of three main documents reporting the findings of this research:

Socio-economic and biodiversity impacts of driven grouse moors in Scotland: Part 1: Socio-economic impacts of driven grouse moors in Scotland - an evidence review of the impacts of driven grouse moors on estate employment, wages, capital assets, etc. as well as on the wider rural business base and on local communities. The socio-economics of a selection of alternative land management models is also considered.

Socio-economic and biodiversity impacts of driven grouse moors in Scotland: Part 2: Biodiversity impacts of driven grouse moors in Scotland – an evidence review of impacts from a range of management activities associated with driven grouse moors, including: muirburn; grazing (sheep and deer); legal predator control; mountain hare management; and a review of ecosystem service delivery by driven grouse moors.

Socio-economic and biodiversity impacts of driven grouse moors in Scotland: Part 3: Use of GIS/remote sensing to identify areas of grouse moors, and to assess potential for alternative land uses – using GIS and remote sensing to estimate the extent, intensity and characteristics of grouse moors in Scotland, including opportunities and constraints for alternative uses.

These three documents are summarised with key findings in:

Socio-economic and biodiversity impacts of driven grouse moors in Scotland: Summary Report

¹ <https://news.gov.scot/news/golden-eagle-deaths>

2 Overview of literature review process

In order to assess the impacts of management activities strongly associated with driven grouse shooting on biodiversity, we undertook a literature review. This built on published evidence and recent reviews, updating these where possible with information from more recent studies.

The term biodiversity can have multiple meanings. For example, Article 2 of the UN Convention on Biological Diversity provides a widely-used definition:

Biological diversity means the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems.

However, for this work we take a broader definition of biodiversity, equating biodiversity to “nature” rather than the stricter CBD definition. We adopt this broader definition because we believe it better aligns with the aims of the project. Using this definition, we do not assume that an increase in biodiversity, for example increases in the number of species or diversity of habitats, is a ‘good thing’ – species poor habitats, for example, can have high conservation value. We aim simply to set out the main patterns of biodiversity response to provide an evidence base which can then be used by others in terms of deciding whether such responses might be considered good or bad.

The literature covered focussed in the first instance on Scotland but where necessary, and in order to plug key evidence gaps, evidence from similar habitats in other areas (for example from northern England) has been drawn upon; where this is the case, we have stated this explicitly.

An initial phase of the literature review was structured in relation to selecting a subset from the following key management activities associated with driven grouse moors:

- Heather burning
- Grazing (sheep and deer)
- Construction of hill tracks
- Use of medication
- Predator control
- Hare control
- Draining or drain blocking
- Use of lead shot.
- Wider environmental impacts (climate change effects of muirburn and peat degradation)

The full process for this initial phase is detailed in Appendix 1 and aims to identify a smaller subset of impacts for focussing on based on: severity of environmental impact, availability of current evidence, or whether the impact is a general issue for driven grouse moors.

We did not consider the issue of raptor persecution; this was discussed with the project Steering Group and it was felt to have already been covered by recent extensive reviews and to be outside our remit in that it is not a legitimate management activity associated with driven grouse shooting.

The subset of management activities agreed with the project Steering Group, and which we subsequently focussed on, are:

- Hare control
- Legal predator control
- Muirburn
- Grazing (sheep and deer)

The method used for undertaking these literature reviews was standardised and based upon the previous peatland muirburn reviews for Climate-x-Change². Details of the specific search process for each sub-section of the review are set out in Appendix 2. We also undertook a 'light touch' overview of the impacts of these management activities on the ecosystem services and benefits provided by areas of land managed for driven grouse shooting.

² Chapman et al. (2017) Muirburn, Peatland and Peat Soils – An evidence assessment of impact. Climate-X-Change, Edinburgh, https://www.climatexchange.org.uk/media/2063/muirburn_peatland_and_peat_soils_-_an_evidence_assessment.pdf

3 Management of mountain hares

3.1 Summary

The conservation and population status of mountain hares remains unclear. While there is emerging evidence of severe localised declines in NE Scotland, a clear and objective assessment is hindered by a reliance on incidental data from surveys that were not designed to monitor mountain hares.

In Scotland mountain hares can be legally killed for sport and population control within the open season. Clearly, killing mountain hares will reduce the local population in the short-term, but the wider and long-term effects will depend on the proportion of mountain hares killed, the spatial scale and the duration over which they are killed combined with how the population responds to the removal of individuals. The (albeit limited) *evidence suggests that sport shooting of mountain hares is likely to have a limited effect on overall and long-term mountain hare conservation status*. This is on the basis that traditional sport shooting of mountain hares is carried out with the intention of sustained sporting and economic interest, and the proportion of hares killed is informed by practitioner knowledge, is proportional to what the local population can sustain, and is limited in spatial extent relative to the distribution of hares. However, we expect the impact of population control (reduction) to be different and depend on the level of control, the spatial and temporal extent and interaction with local and wider hare density, and hare management. We also note that reasons for killing mountain hares are not mutually exclusive.

Although the overall impact of hare population control on hare populations is more likely to be negative than positive, the evidence to assess the impact of different levels of population control at different population densities and at different phases of population growth is currently lacking. The only evidence from Harrison (2011) suggests that at moderate population density mountain hare populations can sustain up to a 40% reduction, but this estimate is based on very limited data and a basic population model and is indicative only. Mountain hare populations have the potential for high population growth rates (Iason 1990), and there is some evidence of density dependant compensation (Knipe et al. 2013). At the same time all the evidence suggests that mountain hare populations in Scotland, as everywhere else they have been studied, show limited dispersal capacity (Harrison 2011) and may therefore be prone to local extinction, though we note that the spatial ecology of mountain hares is not well understood.

Changes in mountain hare numbers could have *potential cascading effects on predators, although the effects are not well researched*. As many predators are generalists the impact might not be severe, but this is not known, and a reduction or loss of mountain hares may result in predators taking a higher proportion of alternative prey (including grouse).

We found little if any evidence to support the killing and population control of mountain hares to protect heather or other vegetation communities, but we note that browsing by mountain hares can suppress tree growth and woodland establishment. Where an alternative browse species such as heather is available, at low population densities mountain hares may not have large impacts on the establishment of native woodland. However, even at low to moderate densities browsing by mountain hares has the potential to suppress tree growth and woodland establishment. There is limited available information in the published literature on the biodiversity impacts of browsing by mountain hares and effects on other sensitive vegetation, and the potential need for associated hare population control. There is also no substantive evidence of competition between grouse and mountain hares for forage, and any depletion of young heather will negatively affect mountain hares more than grouse. Similarly, except under unusual circumstances, there is no compelling evidence to support the population control of mountain hares as part of tick and/or Louping Ill Virus (LIV) control to benefit grouse.

There are *interactive effects of other management activities* in mountain hare populations: legal predator control and muirburn can both benefit mountain hares. However, evidence is mostly correlational and the lack of experimental evidence makes it impossible to identify the relative importance of land use and other biotic and abiotic factors.

3.2 Introduction

Mountain hares are a native species of high conservation concern, an important element of upland biodiversity that is strongly associated with and affected by grouse moor management, and have direct and indirect effects on upland biodiversity. In this section we consider how grouse moor management in general affects mountain hares, the evidence base underpinning different hare management objectives and practices related to driven grouse shooting, and the consequences of this management for hares and wider moorland biodiversity. We therefore draw upon a wide range of relevant published literature as necessary which unless otherwise noted, is peer reviewed.

The mountain hare *Lepus timidus* is listed in Annex V of the EC Habitats Directive (1992), as a species 'of community interest whose taking in the wild and exploitation may be subject to management measures'. Member States are required to ensure that the exploitation of Annex V species 'is compatible with their being maintained at a favourable conservation status'. The Scottish Government's principal objective in managing mountain hare populations in Scotland is to maintain the species in Favourable Conservation Status (FCS) for the purposes of Article 17 reporting under the EC Habitats Directive (JNCC 2013a). The mountain hare in Scotland is a priority species for conservation action under the UK Biodiversity Action Plan (JNCC & DEFRA 2012), and is also on the Scottish Biodiversity List, which means that they are considered by Scottish Ministers to be of 'principal importance' for biodiversity conservation (The Scottish Government 2013). As well as being a native species of conservation concern, mountain hares are a legal game species and can be legally killed in the open-season (1st August – 28th February) for sport, and are also killed to control (i.e. reduce) population densities to protect crops, woodland, forestry and other habitats, and as part of tick control measures (Harrison et al. 2010; Patton et al. 2010). There is concern over the sustainability of current mountain hare management (Harrison et al. 2010, Thompson et al. 2016, Young et al. 2016, Mustin et al. 2018, Watson & Wilson 2018).

Mountain hares are widespread in Scotland but are strongly associated with heather moorland managed for driven grouse shooting where they benefit from some aspects of grouse moor management (Watson & Hewson 1973, Hewson 1984, Patton et al. 2010). Mountain hare densities can be 10 – 100 times greater on heather moorland managed for grouse shooting in eastern Scotland than on heather moorland in the west and arctic-alpine areas (Watson & Hewson 1973). On low moorland in the west of Scotland mountain hares typically occur at less than one per square kilometre; this is compared to typical densities of 50 per square kilometre on grouse moors in the north-east of Scotland, where densities can be in excess of 200 per square kilometre (Watson & Hewson 1973; Newey et al. 2003; Newey et al. 2018).

3.3 Mountain hare population and conservation status

Mountain hares have a strong association with heather moorland managed for driven grouse shooting and can reach very high densities. Consequently, as part of the suite of management activities undertaken to promote driven grouse shooting, and for a variety of goals, mountain hare populations are commonly managed with cascading effects on biodiversity. The biodiversity impacts of mountain hare management will depend on how mountain hare populations respond to that management. In turn this will depend on the wider population and conservation status of mountain hares at local, regional and national scale. In this section we briefly review what is known about the population and conservation status of mountain hares before considering the impacts on biodiversity of mountain hare population management.

The most recent assessment of the population status of UK mammals classed mountain hare as "stable", but likely facing future "declines" though both assessments are associated with low confidence due to limited data (Mathews et al. 2018a, b). Similarly, the last published assessment (covering the period; January 2007 to December 2012) of the conservation status of mountain hares in Scotland, carried out under Article 17 of the EU Habitats Directive, categorised the species as being in "Favourable Conservation Status" (JNCC 2013b). Scottish Natural Heritage is currently carrying out its statutory review of wildlife species and habitats - under its commitment to UK biodiversity reporting

under the EC Habitats Directive for the period 2013-2018 - and is due to report in spring 2019. However, there is no mandatory formal monitoring of mountain hare populations in the UK or Scotland. Consequently, much of our information on hare distributions and numbers comes from surveys or schemes run by non-government organisations, or from research activities. Because of mixed evidence from different sources, the current conservation status of mountain hares in Scotland is not entirely clear.

In their recent high-profile publication Watson & Wilson (2018), report long-term gradual declines from 1954 through to the late 1990's, followed by marked declines on some moorland sites from 1999 onwards. This was based on an analysis of daylight surveys of mountain hares counted across 60 (pooled) moorland and alpine sites spread over the north-east uplands. Similar, but less severe, declines are also reported for alpine sites. On their moorland study sites Watson & Wilson (2018) estimate a 99% decline in mountain hare numbers since counts began in the mid-1950's and attribute the sudden recent declines to the "culling" of mountain hares to control ticks and LIV to benefit grouse. Interpretation of Watson & Wilson (2018) needs to consider that the surveys were designed to count grouse and ptarmigan *Lagopus mutus* and were not designed to monitor mountain hares. In addition, the study sites used were not random nor were the sub-sample of sites counted in one year randomly allocated. As acknowledged by the authors, this means that their study does not allow any inference about what is happening to mountain hare populations elsewhere in Scotland. In addition, as also stated by the authors, the study is correlational and cannot infer cause and effect, only association (Watson & Wilson, 2018).

Two analyses of the British Trust for Ornithology's (BTO) Breeding Bird Survey (BBS) incidental mammal sighting data for mountain hares give somewhat contradictory results. Massimo et al. (2018) assess spatial and temporal changes in mountain hare abundance across the whole of the UK by comparing the mean abundance of mountain hares over the 5-years (1995-99) with mean abundance from the 5-years (2011-15). Their results demonstrate that the mountain hare abundance index showed statistically significant declines of greater than 50% in 34% of 1-km² survey squares, with notable declines identified in the north-east of Scotland (Massimino, Harris & Gillings 2018). In the second analysis of BBS data, Harris et al. (2018) assess the trend in mountain hare sightings, an index of hare abundance, from 1996-2016 and report a non-significant 37% decline in mountain hare sightings. This analysis is based on mountain hare sightings from 52 1-km² squares from across the UK, but there are too few squares with mountain hare sightings to allow a regional level analysis. While any inference from the BBS benefits from a rigorous randomised design and survey protocols, mammals are not the primary survey target and daylight counts of mountain hares by observers on foot have been demonstrated to show poor precision and repeatability (Newey et al. 2018). Furthermore, it is important to note that the comparison of two five-year means 15 years (i.e. approximately 1.5 times the mean periodicity of mountain hare population cycles in NE Scotland) apart may not be entirely appropriate for comparing abundances of mountain hares which, in Scotland, show marked 'population cycles' with a mean periodicity of 9 years (Newey et al. 2007b).

The National Gamebag Census (NGC) administered by the Game & Wildlife Trust (GWCT) is a privately funded repository of game bag (hunting) records that records the number of animals killed during sport shooting and predator control by estates across the UK (Tapper 1992). It was formally established in 1961, though it contains records going back much further; it is a voluntary scheme. Analysis of the number of mountain hares shot per unit area over the period 1961 to 2015 shows no significant change in the numbers of mountain hares reportedly killed by participating estates (1954-2015; change (95% confidence limits) = 65.6% (-1.4 – 149.7)); for comparison with the BBS the period 1995 to 2015 also showed no significant trend (1995-2015; change (95% confidence limits) = 55.7% (-11.7 – 153.4)) (Aebischer et al. 2011). As with the other mountain hare surveys discussed above the NGC only provides an index of hare abundance and not an absolute estimate of hare numbers or density. Gamebag records can be confounded by changes in hunting effort (e.g. Willebrand et al. 2011) and other factors that influence the number of animals killed (e.g. changes to hunting regulations), and the correlation between the number of animals killed and the actual number of animals present

is usually unknown. However hunting statistics are widely used in wildlife research and management (e.g. Elton & Nicholson 1942; Krebs et al., 2001) and red grouse bag records have been shown to be correlated with actual numbers of grouse present (Cattadori et al. 2003). Hewson (1976a) found a strong association between mountain hare bag records in Scotland and the hare density assessed from capture-mark-recapture, and comparison between the NGC and BBS indices show a strong correlation (Noble et al. 2012), all suggesting that while caution is of course needed the NGC appears to provide an index of actual hare numbers at the national scale.

Assessment of the long-term trend in mountain hare numbers and population status of mountain hares is complicated by asynchronous “cyclic” population dynamics, large regional and habitat differences in hare density, and their semi-cryptic nature (Newey et al. 2003, 2008, 2018). The discrepancies between different surveys highlights the difficulties of identifying long term trends in mountain hare populations, a problem augmented by reliance on indices of population abundance or density and incidental data on mountain hares based on surveys primarily intended to survey other species and therefore suboptimal for surveying mountain hares.

3.4 Sport shooting and population control of mountain hares

Mountain hares are a game species that may be legally killed for sport and population control to protect forestry, moorland habitats, woodland regeneration and crops during the open season, and under licence during the closed season (1st March – 31st July), (Tapper 1992, Patton et al. 2010). The number of mountain hares that can be killed in the open season is not regulated and does not require any statutory reporting. Mountain hares are protected by a closed season designed to reduce the risk of killing lactating females with dependant young. Outside of the open season a licence from Scottish Natural Heritage (SNH) is required to legally kill hares (except for humane dispatch), for which a land owner/manager is required to provide a justification, and an indication of numbers to be killed.

We argue it is important to differentiate between killing hares for sport shooting compared to population control because the aims of these two activities differ, though we acknowledge that management objectives are not mutually exclusive and that for example sport shooting may be associated with population control. However, for population control there is an intent to specifically reduce mountain hare density, whereas for sport shooting there is an assumed intent to ensure sustainable sport (Harrison et al. 2010). Killing any number of individuals will obviously reduce and consequently have a negative effect on population numbers. The number of hares killed for sport is usually determined, to some extent at least, by practitioner knowledge and experience of the area and numbers in the present and previous years. Though quantitative evidence is lacking, the only figures available suggest that a typical sport shoot will kill 10-40% of the population (Tapper 1992), though Flux (1970) reports shoots killing over 90% of the population (however, it is not clear what the management objective was). Therefore, with sport shooting the informed and limited number of individuals killed, the limited spatial extent and duration of any hare shooting, and the occurrence of a closed season are assumed to reduce the risk of over exploitation and enable population persistence. However, the formal evidence base for both the decision-making process, setting of bag limits, and understanding of the real impact of killing any given proportion of the population at different stages of the population cycle is lacking. That said traditional sport shooting has been going on a long time and mountain hares have persisted (but see Massimino et al. 2018, Watson & Wilson 2018).

The most obvious biodiversity impact of managing mountain hare populations on areas of moorland managed for driven grouse is the effect on the hares themselves. There is little information on how mountain hare populations respond to different levels of population removal, nor how this might differ in different phases of the population cycle. Mountain hares potentially have a high rate of population growth; female mountain hares can typically produce 4-6 leverets per year, but fecundity and juvenile survival is highly variable between years and prone to stochastic events, with population growth rate being most sensitive to female fecundity (Flux 1970, Hewson 1970, Iason 1990, Harrison 2011 [PhD thesis - chapters 4 and 6]). Clearly, killing individual mountain hares will reduce the local population. However, whether shooting mortality is additive to other causes of mortality or

compensated for by density-dependant processes is not well understood. In one Scottish study Knipe et al. (2013) have demonstrated that mountain hares show density-dependent recruitment, but not density-dependant fecundity, and suggest that an observed significant correlation between population density and juvenile recruitment may provide mountain hare populations with some potential for compensatory juvenile recruitment, although the per capita mortality rates need to be accurately estimated to avoid the risk of over exploitation. A modelling-based study, parametrised with data from a Scottish grouse moor managed for driven grouse shooting, suggests that mountain hare populations may be robust to a maximum of 40% of individuals removed annually (Harrison 2011 [Chapter 6]). However, population persistence is sensitive to population size and age-biased shooting mortality and risk of population extinction increases with declining population size and increased shooting mortality of juveniles (Harrison 2011 [Chapter 6]).

Movement and particularly dispersal are important processes in maintaining population viability. Especially in populations that exist in (increasingly) fragmented landscapes. Mountain hares on managed moorland in Scotland appear to have limited movement and offspring dispersal (Hulbert et al. 1996, Rao et al. 2003d, Harrison 2011), a phenomenon also noted for mountain hares in Ireland and Scandinavia (Wolfe & Hayden 1996, Dahl 2005, Dahl & Willebrand 2005, Kauhala et al. 2005). Limited movement and dispersal capacity can greatly increase the risk of local extinction in the face of over shooting, and this risk is increased in species that show cyclic or unstable population dynamics and which are prone to stochastic effects (Sutherland 2001, Lande et al. 2003). However, we note that the spatial ecology of mountain hares in Scotland is poorly understood, and that there appear to be genuine differences between practitioner experience and the scientific evidence concerning the movement ecology of hares.

3.5 Wider biodiversity impacts of mountain hare management

3.5.1 Mountain hares as prey

One of the obvious wider biodiversity impacts of reducing mountain hare numbers as part of the management regime for driven grouse shooting is the effects on those other species for which mountain hares are prey. Mountain hares are prey to a wide range of predators; fox (*Vulpes vulpes*), wild cat (*Felis silvestris*), stoat (*Mustela erminea*), weasel (*Mustela nivalis*), buzzard (*Buteo buteo*), hen harrier (*Circus cyaneus*), and golden eagle (*Aquila chrysaetos*) all prey on mountain hares in Scotland (Flux 1970, Hewson 1976a, Watson, Leitch & Rae 1993, Watson 1997, Whitfield et al. 2013). In one study carried out on driven grouse moor in the north-eastern Cairngorms, predation accounted for 14–15% of adult mortality and 34–56% of juvenile mortality; foxes were responsible for 60–90% of all deaths due to predation (Flux 1970). Hares can constitute over a third of a golden eagle's diet, and up to 15 % of a white-tailed eagle's (Watson, Leitch & Rae 1993, Watson 1997, Whitfield et al. 2013). Therefore, changes in mountain hare numbers could have cascading effects on other predators, although the effects are not well researched (Flux 1970, Hewson 1976a, Watson et al. 1993, Watson 1997). As many predators are generalists the impact might not be severe, but this is not known, and a reduction or loss of mountain hares may result in predators taking a higher proportion of alternative prey (including grouse).

3.5.2 Hare browsing impacts on biodiversity

Mountain hares are herbivores, and generally far more numerous on managed grouse moors than elsewhere. In some circumstances, at moderate to high population densities, browsing by mountain hares can potentially have a negative impact on woodland regeneration, forestry, and sensitive plant species and communities (Gill 1992, Rao et al. 2003a, b). However, studies on the effects of woodland planting on habitat selection by mountain hares on heather moorland in central and north-east Scotland show that mountain hares do not actively select areas planted with Scots pine *Pinus sylvestris* or birch *Betula pendula* seedlings over adjacent control areas of heather moorland (Rao et al. 2003a, b, d). The same experiment also suggests that where an alternative browse species such as heather *C. vulgaris* is widely available, mountain hares may not have a large impact on the establishment of native woodland (Rao et al. 2003c), and that any browsing damage to trees by mountain hares is most likely

to be a function of the local abundance of mountain hares, rather than a result of active preference on the part of hares (Rao et al. 2003d). However, even at low to moderate densities, browsing by mountain hares has the potential to suppress woodland establishment, and thereby this component of upland biodiversity, on heather moorland.

There is no doubt that sensitive vegetation communities and species, such as montane willows *Salix* ssp. dominated montane scrub and Dwarf juniper *Juniperus communis nana*, are affected by herbivore damage. Although mountain hares do browse these species the impact of browsing by mountain hares is unknown (Gilbert et al. 1997, Hester 1997). In some cases mountain hares are killed to reduce hare densities and associated browsing in order to protect sensitive plant communities and species. There is limited available information in the published literature on the biodiversity impacts of browsing by mountain hares, its effects on sensitive vegetation, and the potential need for hare population control. We therefore approached SNH directly and received the following information:

- “1) There have been some instances in which mountain hare have been recorded as having negative impacts on open-ground vegetation in designated sites, but these are localised, few in number, and impacts occur in combination with impacts from other herbivores such as deer and sheep. Positive and neutral impacts of mountain hare on habitats have also been recorded on designated sites.
- 2) SNH has not asked any estate to control mountain hare because of grazing issues.
- 3) SNH has issued out of season licences for control of mountain hare at several locations, to prevent serious damage to newly planted or regenerating woodland. One of those locations may have affected a designated site. No licences have been issued for any other grazing impact.
- 4) While it’s not inconceivable that there could be circumstances in which SNH might seek control of mountain hare in order to protect sensitive open-ground habitats or species, the question is hypothetical and not one that we’ve had any need to consider to date.”

(Upland Adviser, SNH, personal communication [received 30/08/2018]).

Heather is an important food for grouse and mountain hares: it constitutes 60-100% of the diet of grouse and, though mountain hare diet in summer includes a large proportion of grasses, sedges, and rushes, heather comprises from between 30-90% of the diet of mountain hares (Moss & Miller 1976, Savory 1986, Iason & Van Wieren 1999, Hulbert et al. 2001, Rao et al. 2003c). Heather is the primary dietary component of both grouse and hares in the winter, and both species tend to prefer younger and more nutritious heather in spring; the availability of young heather is particularly important to the breeding success of female grouse (Moss & Miller 1976). Though there is some evidence that mountain hares may deplete the availability of young heather to grouse in the spring, and although this has been proposed as a mechanism for competition between the species, there is no substantive evidence of competition between grouse and mountain hares, and any depletion of young heather will negatively affect mountain hares more than grouse (Moss & Miller 1976, Savory 1986).

Earlier studies (Grant *et al.* 1978) concluded that browsing that removes more than 40% of the annual growth of heather can degrade the heather quality, though more recent work suggests that these previous estimates of the critical level of offtake are too high and that a figure of around 20% is more appropriate (Pakeman & Nolan 2009). We estimate that on average a single adult mountain hare will remove around 75 kg of heather per year. If we assume a typical value of around 148,000 kg km⁻² of annual biomass production for heather managed for grouse shooting at 450 m a.s.l. (Armstrong et al. 1997 (Appendix 7)), then a population of 281 mountain hares per square kilometre (the highest density recorded by Watson & Hewson, 1973) would remove an estimated 21,075 kg of heather biomass, or around 14% of annual heather production on a typical heather moorland. This calculation is based on conservative estimates of the amount of plant material a mountain hare needs to meet its energetic and nutrient requirements, and it is likely that hares will consume less than assumed here. While browsing by mountain hares has to be seen in the context of a wider community of herbivores often present in the Scottish uplands, based on the calculations presented here there is no evidence that

browsing by mountain hares alone will have deleterious effect on heather under a range of normal conditions.

3.5.3 Ticks and louping-ill

Part of the expected biodiversity impacts of reducing mountain hare numbers – and a reason for hare population control - is a reduction in tick numbers and associated tick-borne diseases. Ticks are a component of moorland biodiversity. It is therefore relevant to consider the impacts of hare population control on tick populations and disease risk.

Mountain hares and sheep carry ticks and both have been implicated in the transmission of the louping ill virus (LIV) to grouse. LIV is a flavivirus transmitted by sheep ticks *Ixodes ricinus* and can cause high mortality in infected grouse chicks (Reid 1975) reducing grouse densities and the associated revenues from shooting (Laurenson et al. 2003). Therefore, controlling LIV is considered to be important for the continued viability of estates managed for grouse shooting (Reid 1975, Reid et al. 1978, Hudson 1992). Although mountain hares do not show clinical symptoms of LIV, they are hosts for ticks (Laurenson et al. 2003) and can play a role in tick-to-tick transmission of louping-ill (Jones et al. 1997). Communication of research findings to moorland managers, and the associated proposal that culling wildlife hosts, including mountain hares, could be an effective management strategy to control ticks and LIV (e.g. Smith 2009), has led to increased culling of mountain hares in some areas of Scotland (Patton et al. 2010, Watson & Wilson 2018). There is evidence that an increasing proportion of hares are now being killed as part of tick control programmes, with the intention of suppressing mountain hare densities to low or very low numbers, in some cases over large areas of ground (Patton et al. 2010, Gilbert 2016, Watson & Wilson 2018).

The only published evidence to support population control of mountain hares to reduce ticks and LIV to benefit grouse comes from the Lochindorb study, which showed that reducing hares was associated with fewer ticks, lower LIV prevalence, and increased grouse bag (Laurenson et al. 2003). The Lochindorb study has been criticised for lack of replication and any meaningful experimental control, and for potentially confounding treatments (Cope et al. 2004, Laurenson et al. 2004, Harrison et al. 2010). Two independent reviews of evidence of the efficacy of reducing hare numbers as part of tick LIV control to benefit grouse have concluded that;

“that there is no compelling evidence base to suggest culling mountain hares might increase red grouse densities” (Harrison et al. 2010), and

“Although, tick control measures can sometimes improve grouse chick production (Laurenson et al. 2003), there is no clear evidence that mountain hare culls serve to increase red grouse densities, and in any case both ticks and louping-ill virus persist when and where alternative tick hosts such as red deer are present at even low densities (Gilbert et al. 2001, Harrison et al. 2010).” (Werritty et al. 2015).

This interpretation of the evidence appears to be accepted by some of the main organisations representing the land management sector (including driven grouse moor interests), and is captured in the joint SNH-GWCT-SLE statement on voluntary restraint which clearly acknowledges the lack of evidence to support population control of mountain hares to benefit grouse – “Large-scale culls of mountain hares to reduce tick loads, in order to benefit grouse and other bird survival, will only be effective when other hosts are absent, or their ability to host ticks are similarly reduced. This will not be the case for many estates in Scotland” (SNH et al. 2014).

3.6 Interactions of hare population management with muirburn and predator control

In Scotland, moorland management for grouse production involves control of a number of predators (see the section on Legal Predator Control), especially foxes, and routine legal predator control carried out as part of grouse moor management would be expected to benefit mountain hares.

In addition traditional moorland management for grouse involves the rotational burning – muirburn - of small patches (< 2 ha) of old heather to promote the growth of young heather, thus producing a

habitat mosaic of different aged heather (Moss & Miller, 1976). Although mountain hares are flexible foragers and prefer high quality grazing when available, in Scotland bulk browsing of heather forms no less than 50% of their diet in winter when grass and herbaceous vegetation are not available. Studies in the Scottish uplands have shown that mountain hares prefer to browse young short heather, which is more nutritious, and contains more nitrogen and fewer secondary plant compounds than does old heather (Moss, Miller & Allen 1972, Moss & Miller 1976, Hewson 1976b, 1984, 1989, Savory 1986), while tall heather provides shelter from weather and predators (Thirgood & Hewson 1987, Hewson 1989). Muirburn, in particular the burning of small patches typical of grouse moors as opposed to large areas as practiced to promote grass growth for sheep production, is therefore likely to be beneficial to mountain hares by providing a fine mosaic of young and old heather.

There is good correlational (but no experimental) evidence that mountain hares benefit from predator control and habitat management (muirburn) carried out to support high densities of grouse for driven shooting (Watson et al. 1973, Hewson 1984). However, the lack of experimental evidence makes it impossible to identify the relative importance of land use and other biotic and abiotic factors. For example, mountain hare numbers have also been shown to be influenced by underlying geology, with hares being more numerous on heather moorland overlying base rich (diorite and epidiorite) rocks than those overlying granite (Watson & Hewson 1973). The concentration of driven grouse moors in the north-east of Scotland, where the climate is generally colder and drier and which favours heather compared to the cooler and wetter climate of the west Scotland, also confounds direct comparison between hare numbers and land use (Watson & Hewson 1973).

4 Legal predator control

4.1 Summary

Two experimental studies, one from Scotland and one from northern England, but both from moorland managed for grouse shooting, suggest that the impacts of legal predator control (i.e. control of species such as crows (*Corvus* sp and *Cornix* spp.), fox (*Vulpes Vulpes*) and stoat) vary between bird species, and that predator control tended to increase breeding success more than population density (Parr, 1993, Fletcher et al. 2010). Correlational evidence also strongly suggests that *predator control can have positive biodiversity effects by increasing breeding success and numbers of some species of ground nesting bird*, particularly upland waders, that breed on moorland, *but effects can be negative for other species*. There is also evidence that predator control favours a slightly different bird community compared to other management activities thereby promoting increased beta-diversity (i.e. overall greater number of species at a landscape scale) (Newey et al. 2016b).

Predator control will, by definition, tend to reduce local populations of controlled species, sometimes dramatically. However, *the link between legal predator control and population change at the wider geographic scale is unknown* and the effect of systematic and sustained predator control on the species that are controlled is not well understood. *Predators carry out a range of ecological functions, and again the impact of reduced abundance of predator species, some of which are also important scavengers, is unknown*. The carcass remains of killed animals provide a source of energy and nutrients for a wide range of organisms with cascading trophic effects that influence soil chemistry, vegetation, invertebrate and vertebrate communities (Fielding et al. 2014). The removal of keystone predators can also influence the distribution and abundance of smaller predators (meso-predators) leading to the so called meso-predator release (greater numbers of smaller predatory species) with positive and negative biodiversity effects. However, and again in the context of predator control on grouse moors in Scotland, *there is a distinct lack of knowledge about how removal of one, or a range of, predators affects other predators and the wider food web. Overall the effects of predator control on wider biodiversity are poorly understood*.

4.2 Introduction

Legal predator control is common across Europe, in relation to the management of important socio-economic game birds such as red-legged partridge (*Alectoris rufa*), pheasant (*Phasianus colchicus*) and red grouse (*Lagopus lagopus scoticus*) (e.g. Mustin et al. 2018). In Scotland legal control of avian (crows *Corvus* sp and *Cornix* spp.), and mammalian predators (red fox *Vulpes vulpes*, stoat *Mustela erminea* and weasel *Mustela nivalis*), and is a common practice on estates managed for recreational shooting to reduce predation pressure, increase survival and ultimately the number of red grouse that can be shot (Hudson 1992, Thirgood et al. 2000). Control of these generalist predators benefits grouse and some other species of ground nesting birds and can also have wider positive and negative biodiversity effects (see; Cote & Sutherland 1997, Thompson et al. 2016, Mustin et al. 2018, Roos et al. 2018 for recent reviews). In this section we review the current literature to explore the impact on biodiversity of legal predator control carried out on grouse moors managed for driven shooting. Illegal predator control is a major issue and has been shown to limit the national range and population size of some species (see; Cote & Sutherland 1997, Mustin et al. 2018, Roos et al. 2018, Thompson et al. 2016, Young et al. 2016 for recent reviews); however this topic is outwith the scope of our review (as mentioned in Section 2). Similarly the topic of bycatch is also not covered here.

4.3 Experimental Studies

There are only two studies that have experimentally reduced predator numbers and monitored the effect on prey species (Parr 1993, Fletcher et al. 2010). At one moorland study site in NE Scotland Parr (1993) experimentally removed (killed) carrion crows (*Corvus corone*) and common gull (*Larus canus*) to assess the effect of egg predation by these avian predators on golden plovers (*Pluvialis apricaria*) nesting success and numbers (although the focus was on golden plover, other species lapwing *Vanellus vanellus*, curlew *Numenius arquata*, redshank *Tringa totanus* and oyster catcher *Haematopus*

ostralegus were also monitored). The numbers of crows and gulls, and predation by these species, were reduced at the study site and in the surrounding area. Lapwing, curlew and redshank, but not golden plover or oyster catcher, showed increased hatching success during the period that crows and gulls were controlled (Parr 1993). However, wader numbers did not increase, apparently due to increased predation by foxes, which were not controlled as part of the experiment.

Over the course of an 8-year-field experiment on moorland in northern England, Fletcher et al. (2010) manipulated the abundance of legally controllable predators, to represent the level of legal predator control that would be carried out on working grouse moor. They monitored the subsequent changes in both the breeding success and abundance of five ground-nesting bird species lapwing, golden plover, curlew, red grouse and meadow pipit (*Anthus pratensis*) and the abundance of snipe (*Gallinago gallinago*) and skylark (*Alauda arvensis*). Legal predator control reduced fox numbers by 43% and carrion crow by 78% but predator control had no detectable effect on the numbers of stoats and weasels, species which were only present at very low numbers from the start of the experiment. Reductions in foxes and crows were associated with an average threefold increase in breeding success of lapwing, golden plover, curlew, red grouse and meadow pipit. Predator control was also associated with annual increases in breeding numbers of 14% or more of lapwing, curlew, golden plover and red grouse. In the absence of predator control, breeding numbers of lapwing, curlew, golden plover and red grouse all decreased by 17% or more per annum (Fletcher et al. 2010). Although carried out in northern England the study system is similar to that found in many parts of Scotland, and the experimental design, whereby treatment and control were swapped over half way through the experiment, demonstrates that legal predator control can increase breeding success and breeding numbers of some upland bird species with a positive effect on biodiversity. However, predator control was associated with local declines in predator species themselves, and hence a negative effect on predator biodiversity.

4.4 Correlational Studies

The difficulties of carrying out predator reduction experiments mean that most studies investigating the biodiversity effects of legal predator control are correlational, whereby the association between the factors or variables of interest are implied by assessing the response along a gradient of conditions. Correlational studies provide valuable and meaningful insights, often at much larger spatial scales than do experiments, but it is not possible to assume a cause and effect relationship, in contrast to well-designed experiments, because there is no unmanipulated control to act as a point of comparison.

Tharme et al. (2001) assessed whether population densities of 11 species of breeding moorland birds, including upland waders of conservation concern, differed between heather-dominated moorland managed for red grouse shooting and other moorland with similar vegetation but not managed for grouse shooting. Although this study found that densities of breeding golden plover and lapwing were higher on moorland managed for red grouse shooting, including legal predator control, the study was not designed to separate out the effects of specific management practices as opposed to the overall effect of grouse moor management (Tharme et al. 2001). In a similar study looking at the effect of geographic, environmental and site level management (including legal predator control, indexed as the mean density of full-time game keepers) Buchanan et al. (2017) identified a positive correlation between keeper density and the abundance of red grouse, curlew, and golden plover. Both studies provide evidence that grouse moor management can have a positive biodiversity impact on moorland ground nesting birds, but do not demonstrate a link between legal predator control and positive biodiversity effects *per se*.

Investigating changes in curlew numbers and breeding success at study sites in the south Pennines and southern Scotland in relation to game keeper density (as a surrogate for predator control intensity) and woodland cover, Douglas et al. (2014) showed that population change and breeding success were positively correlated with game keeper density (and negatively correlated with woodland cover). Douglas et al. (2014) provide evidence that predator control (indexed by game

keeper density) has a positive biodiversity outcome in terms of increased numbers of the curlew and increased breeding success.

Assessing the effects of different land uses (grouse moor, deer stalking, sheep production, and biodiversity conservation) and management practices (muirburn and legal predator control) on avian diversity and community composition, Newey et al. (2016b) reported that avian and mammalian predator control was more prevalent among grouse shooting estates than estates with other dominant management objectives. However, there were no significant differences in species richness or species diversity between estates primarily managed for red grouse shooting, deer stalking, sheep production or biodiversity conservation (Newey et al. 2016b). Neither avian species richness nor diversity varied significantly with predator control (or intensity of muirburn) (Newey et al. 2016b). Analysis of community composition however revealed a more nuanced effect. Predator control itself did not have a significant effect on community composition. However, grouse moor management was associated with significant effects on absolute and relative abundance of species, and on community composition. Specifically it led to species assemblages characterised by a greater abundance of wading birds such as curlew, golden plover, common sandpiper (*Actitis hypoleucos*), as well as black headed gull (*Chroicocephalus ridibundus*), buzzard (*Buteo buteo*), short eared owl (*Asio flammeus*), red grouse and meadow pipit, and negatively associated with corvids, merlin (*Falco columbarius*) and some passerine species (Newey et al. 2016b).

Due to illegal persecution, hen harriers (*Circus cyaneus*) tend to be negatively associated with grouse moors (Etheridge, et al. 1997). As ground nesting birds hen harriers may benefit from control of red fox and other generalist predators. However, in a reanalysis of previous data (Etheridge, et al. 1997) Green & Etheridge (1999) concluded that there was no clear evidence for beneficial effects of the control of foxes and other predators on hen harrier nest success.

Contrary to this finding, however, and based on an analysis of changes in hen harrier breeding attempts and productivity over the course of the Langholm study, Baines & Richardson (2013) report that after grouse management stopped in 1999, carrion crow and red fox numbers increased and numbers of female harriers dropped to below five from 2002 onwards. The mean number of breeding females was higher, clutch survival was higher and overall productivity were all higher when the moor was managed as a grouse moor, including muirburn and legal predator control (1992–1999) than when there was no grouse moor management (2000–2007). Over the course of the study 55% of breeding attempts where the fate was known failed due to predation by red fox (Baines & Richardson 2013). This study supports the hypothesis that in the absence of illegal persecution, grouse moor management can benefit harriers by legally reducing generalist predators that may predate their clutches, chicks or even adults themselves (Baines & Richardson 2013). With the reinstatement of grouse moor management, including routine legal predator control, at Langholm in 2008, and subsequent monitoring of red grouse, red fox, carrion crow and hen harrier numbers, Ludwig et al. (2017) report a decrease in indices of fox and crow abundance and that there were associated increases in grouse numbers and hen harrier abundance and breeding success. Ludwig et al. (2017) argue that these results show that some components of biodiversity, in this case red grouse and hen harriers, can benefit from grouse moor management; the declines in fox and crows and associated increases in grouse and hen harriers supports this assertion.

While these correlational studies suggest that heather moorland managed for grouse shooting has biodiversity benefits for some species of ground nesting birds, particularly species of upland waders that are in serious decline, none show a direct link between legal predator control and increased biodiversity for the areas and species that have been studied. This may be a consequence of the correlational nature of these studies, or the fact that the biodiversity benefits of grouse moor are synergistic rather than down to one specific management practice, in this case legal predator control.

4.5 Review based studies

The widespread interest, and controversy, around legal predator control as a biodiversity management tool has led to a number of review studies that synthesise a wide body of evidence on

the role of predators in limiting prey populations, and the effectiveness and consequences of predator removal (Cote & Sutherland 1997, Mustin et al. 2018, Roos et al. 2018). These review studies do not relate directly to the biodiversity impacts of predator control on grouse moors in Scotland, but we think it is useful to draw attention to these reviews here. In particular Mustin et al. (2018) report a pertinent finding in relation to the biodiversity impacts of legal predator control; they found that the effects of legal predator control were most often positive (96% of effects) or benign for non-target (i.e. non-game) species.

4.6 Impact of predator control on predator populations and wider biodiversity

The afore-mentioned studies have looked, in different ways, at the biodiversity impact of legal predator control on particular species of economic or conservation interest, but few have assessed how predator control effects the controlled predator species, predator biodiversity, and the cascading effects of reduced predator abundance and diversity. Following the experimental removal of crows and gulls Parr (1993) reported lower numbers of these birds on his study site post removal, but that crow and not gull numbers increased to base line numbers each year, suggesting that crows immigrated into the study area each spring and any impact on numbers was limited, but that gulls appeared to show limited immigration and were reduced to low numbers over the course of the study (Parr 1993). Fletcher et al. (2010) show that predator control was associated with a 43% decline in fox numbers and 78% decline in crow numbers on the study site, though the impact on the wider populations and biodiversity is not known. At Langholm crows occurred at low numbers while the moor was managed for grouse, but increased after 1999 when routine killing of crows on the moor largely stopped. From 2000 onwards, crows were four times more numerous than in the period when gamekeepers were present, and average fox abundance (indexed by scat abundance) increased fourfold between 2002 and 2005 before levelling-off (Baines & Richardson 2013). In addition Ludwig et al. (2017) report that 189 (+/- 22) foxes, and 260 (+/-22) carrion crows were killed per annum on Langholm when grouse moor management was reinstated in 2008, and that fox density was reduced from 0.11 (+/- 0.05) km⁻² when there was no predator management, to 0.06 (+/- 0.02) km⁻² during the period 2009-2015 when predator control was carried out. Together this limited evidence suggests that predator control, not surprisingly, reduces local predator numbers.

Table 1 Summary of changes in the gamebag records for red fox, stoat and weasel for the True Uplands of Scotland. Source: Aebischer, N.J., Davey, P.D. & Kingdon, N.G. (2011). National Gamebag Census: Mammal Trends to 2009. Game & Wildlife Conservation Trust, Fordingbridge (<http://www.gwct.org.uk/ngcmammals>)

Species	Mean Percentage Change (95% Confidence Limits)		
	1961-2009	1984-2009	1995-2009
Red fox (n = 170)	102* (17 – 227)	-10 (-49 – 45)	-27* (-42 – -9)
Stoat (n = 137)	62 (-12 – 237)	87* (28 – 157)	26* (7 – 49)
Weasel (n = 137)	37 (-22 – 127)	53* (3 – 168)	52* (12 – 109)

* significant change at $P < 0.05$

Assessment of the impact of legal predator control on the wider predator populations is hampered by a lack of any dedicated monitoring of these species. The information that is available comes from the National Gamebag Census (NGC), and incidental mammal sightings recorded as part of the Breeding Bird Survey (BBS). While these surveys cannot provide evidence about the effects of legal predator control on the wider populations of legally controlled species, they provide important context and in the case of the NGC there is a clear link between legal predator control and the number of predators killed. At the UK level the recent review of the population and conservation status of UK mammals categorised the red fox as “stable” but concluded there was insufficient information to categorise the status of stoat and weasel (Mathews et al. 2018a, b). The NGC shows that the trend in the number of

foxes killed in Scotland depends on region (lowlands, intermediate uplands and islands, and the true uplands) and time scale. As grouse moor management is confined to heather moorland in the true uplands, here we only consider trends from this region. Though fox bag records show a long-term significant increase, more recent trends show declines, with records from 1995-2009 showing significant declines (Table 1) (Aebischer et al. 2011). Again, focusing on the true uplands bag records, stoat and weasel bag records both show sustained increases (Table 1) (Aebischer et al. 2011).

Mammal trends from the BBS are only available for red fox at the UK level, and show that the number of foxes seen over the period 1996-2016 has declined significantly by 41% (-50 to -30) (Harris et al. 2018). An analysis of fox sightings collected during the BBS looking at spatial and temporal trends also identified a substantial and significant 34% decline in the number of survey squares in which foxes were seen, and note the low or zero abundance of foxes in some upland areas (principally the central and NW Highlands) of Scotland (Massimino et al. 2018). The BBS bird data shows the abundances of both carrion and hooded crows have declined over the last 10 and 21 years, with carrion crows showing a significant 16% decline in Scotland over the last 10 years (2006-2016) (Harris et al. 2018). The NGC shows that the number of crows (the NGC groups carrion and hooded crows together) reportedly killed across the whole of the UK have doubled over the 1960-2010 period (Aebischer et al. 2011). However, although remaining the best information available, neither the NGC or BBS can be considered ideal survey platforms for assessing changes in the distribution and numbers of foxes and both are associated with wide confidence intervals. Indeed, both the NGC and BBS only provide indices of animal numbers and how these indices relate to actual numbers is unknown.

Many predators prey on or compete with other predators and directly or indirectly affect the distribution, abundance and behaviour of other predators. Removal of larger predators can result in mesopredator release (the increase in distribution and/or abundance of smaller species of predator due to lower predation pressure or reduced competition following the removal of larger predators), with potentially positive and negative biodiversity effects (e.g. Ritchie & Johnson 2009). In addition, predators provide a well dispersed and regular supply of partially consumed carcasses to scavengers, resulting in increased microbial, invertebrate and vertebrate scavenger biodiversity (for some non-UK examples see; Selva et al. (2005), and Wilmers et al. (2003), and popular articles; Fielding et al. (2016) and Newey et al. (2016a) for examples from Scottish uplands). Many predatory species are also scavengers, indeed red fox and carrion crow, two of the most widely legally controlled predators are also scavengers. Scavengers play important, but largely unexplored, roles in maintaining and driving biodiversity with cascading effects on soil, below ground processes, vegetation, and nutrient recycling with direct and indirect effects on biodiversity, but these effects have not been well quantified in Scottish upland ecosystems (Milner et al. 2002, Fielding et al. 2014).

5 Muirburn

5.1 Summary

Muirburn simply means burning vegetation in moorland areas. In heather-dominated areas, muirburn is carried out to rejuvenate the main plant species, heather, providing more nutritious young shoots for grazing animals. In areas dominated by grasses such as *Molinia*, regular burning removes dead material, making the new grass shoots easier for grazers to access. In the UK, there is currently a particularly strong association between muirburn and habitat management for red grouse, but it is also used in some moorland areas for management of deer and livestock grazing. On moorland areas managed for driven grouse (the focus of this review), rotational muirburn is carried out to create small patches of heather of different ages to produce a mosaic of patches of ground containing young, more nutritious heather stems for grouse to eat and patches of taller heather for cover. There is both guidance and regulation relating to muirburn (Muirburn Code 2017, SRDP and more).

UK moorlands are an amalgam of 'natural' (beyond the climatic limits for tree/scrub growth) and 'cultural' – the latter being largely a product of regular muirburn (and/or grazing), the former not so. This review focuses on muirburn and therefore almost all the research quoted has been carried out within the 'cultural' moorland zone where regular muirburn is carried out.

Biodiversity impacts - overview. There has been a great deal of research on muirburn impacts (on above-ground biodiversity) with a wide diversity of often contradictory findings. There is strong evidence from many papers that the major determinant of any reported increases in biodiversity is the mosaic of different ages of burn giving a mix of habitat structures, as well as post-fire 'good seedbeds' for germination. Undoubtedly, muirburn can in some cases cause detrimental effects on biodiversity (and other components of the system) - *fire intensity seems to be critical in determining severity of impact*, but most studies have not recorded this - the high degree of uncertainty and controversy concerning muirburn impacts is probably directly related to this paucity of connected information from fire intensity through to measured impacts. There is strong evidence that a key issue in terms of impacts of muirburn is whether or not the fire has burned into the moss/litter layer/soil/peat - in that order, it greatly increases the likelihood of detrimental impacts, not just on biodiversity. Muirburn impacts can also differ according to the type of moorland. Strongest (but much is still inconclusive) evidence for a greater likelihood of long-term *detrimental* impacts comes from blanket bog/wet heath areas, and it has been widely assumed that regular muirburn is detrimental to peat-forming species such as *Sphagnum*. However, this is not conclusive either as several studies have found the opposite, including the long term (60 years) experimental study that followed burnt v unburnt areas - both *Eriophorum* and *Sphagnum* (especially *S. capillifolium*) became more abundant in frequently burned plots than unburned. There is moderate evidence suggesting that both different *Sphagnum* species and different growth stages are differentially affected by fire. In addition, not all *Sphagnum* species are considered indicative of a bog in good health (some species are important peat-formers, others are not) so this also needs to be considered when assessing individual *Sphagnum* species responses to muirburn.

We found no direct studies on impacts of muirburn on below-ground biodiversity, apart from seed bank studies. More generally (i.e. below-ground impacts in general), fire severity is again a key issue: impacts on soil structure/properties (and carbon in particular) tend to be more severe (sometimes catastrophic) under more intense, longer duration fires igniting dry soil/peat. Fires penetrating the moss/litter soil are likely to destroy much of the seed bank, which could result in a very different post-fire plant species composition (comprising vegetative regrowth and germination from seeds arriving in the seed rain as opposed to germinating from the soil seedbank). If the fire does not penetrate the moss layer then it seems unlikely that there will be any major direct below-ground biodiversity impacts (but data are scarce and inconclusive).

Biodiversity impacts of burning v not burning heather moorland. It was traditionally thought that regular muirburn was necessary for *Calluna* to remain dominant, but this has been disproved at least for some moorland areas where heather remained dominant (through stem layering/rooting) for at

least 40-60 years without burning. It is not known what proportion of Scotland's moorland has never been burnt so this a key evidence gap, and we cannot even estimate what proportion of moorland might remain heather-dominated long term in the complete absence of fire. This information would greatly inform the debate about the 'need' or otherwise of regular moorland burning in terms of maintaining *Calluna* dominance (we consider that the 'benefit' of muirburn in terms of greater nutritive value of young heather shoots following fire is well established in the literature).

There is relatively little comparative information on impacts of *heather burning versus cutting* and from the few studies found, the differences are apparently not simple: old heather stands tend to regenerate better after fire than cutting (strongly dependent on seed germination and seedbed), but the few data available indicate that younger heather regenerates better under cutting than burning. Discussions on relative impacts of muirburn v cutting on other elements of biodiversity are mostly speculative as there is so little information available.

Climate change and muirburn. The risk of uncontrolled fire is predicted to increase in Scotland as the summers are predicted to become hotter and drier. Various data sources from both Scotland and England quote varying proportions of wildfires starting from muirburns. Given this connection, it is critically important that the Muirburn Code and regulation updates relating to muirburn use the best available evidence to minimise the chance of muirburn fires getting out of control. This includes explicitly addressing predicted climate-related changes of strong relevance to muirburn intensity/severity into the future. Muirburn (and grazing and cutting) can also play a role in reducing fuel loads and possibly reducing the incidence or at least the severity (temperature) of wildfires, although there is a lack of data demonstrating how these management actions can be combined to best effect.

5.2 Introduction

Muirburn simply means burning vegetation in moorland areas. In heather-dominated areas, muirburn is carried out to rejuvenate the main plant species, heather, providing more nutritious young shoots for grazing animals. In areas dominated by grasses such as *Molinia*, regular burning removes dead material making the new grass shoots easier for grazers to access. In the UK, there is currently a particularly strong association between muirburn and habitat management for red grouse, but it is also used in some moorland areas for management of deer and livestock grazing. On moorland areas managed for driven grouse shooting (the focus of this review), rotational muirburn is carried out to create small patches of heather of different ages to produce a mosaic of patches of ground containing young, more nutritious heather stems for grouse to eat and patches of taller heather for cover. There is both guidance and regulation relating to muirburn (Muirburn Code 2017, SRDP and more).

UK moorlands are an amalgam of 'natural' (beyond the climatic limits for tree/scrub growth) and 'cultural' habitats – the latter being largely a product of regular muirburn (and/or grazing), the former not so. This review focuses on muirburn (but does also quote wildfire research findings where relevant) and therefore almost all the research quoted has been carried out within the 'cultural' moorland zone where regular muirburn is carried out.

5.3 Muirburn impacts in context – the importance of fire characteristics

Reviewing the extensive literature on muirburn impacts rapidly reveals the importance of fire characteristics in determining biodiversity and wider ecosystem impacts, yet in much of the debate and disagreement over 'contradictory findings', this is sometimes glossed over or overlooked. We therefore consider three important elements of fire here before looking at the information available on biodiversity impacts, as it sets that work in context.

In our view, fire intensity/severity is absolutely critical in terms of muirburn impacts and this is often overlooked. Very few fire studies have included detailed measurements of fire severity linked through to impacts (e.g. Davies et al. 2016a, Davies & Legg 2016), and therefore it is impossible to link most reported fire impacts to the actual characteristics of the fire causing those impacts. The best available data in this respect is from Davies and Legg and colleagues (many papers – for a recent summary see

Davies et al. 2016b), but Lukenbach et al. (2016) also give important findings in this respect (from Canadian peatland); and there is a strong reliance on modelling work to predict likely impacts from different types of fires. This work has identified some key factors affecting fire intensity/severity: (a) fuel load: there are strong links between severity of burn and fuel load (e.g. Davies et al 2016a), and longer rotation burning generally leads to greater fuel loads (e.g. Milligan et al. 2018); (b) soil/vegetation moisture and weather conditions – these factors are critical for fire severity (e.g. Grau-Andres et al. 2018) and correlate with time of year. Most muirburns happen in winter/early spring following the Muirburn Code – this is normally the least damaging time of year (minimal soil heating and high moisture, reducing likelihood of ignition of moss/peat). Clearly, a combination of high fuel load and hot, dry conditions (which can also happen within the approved muirburn season) is the most likely to result in a more severe fire, so predicted changes in climate are a cause of concern in this respect (see later discussion).

Our understanding of fire frequency impacts on biodiversity is based on relatively little data and some key modelling work; few studies specifically address biodiversity impacts and some findings are contradictory. We propose that some of these apparent contradictions probably also relate to (usually undocumented) differences in fire severity in the different studies. For example, Milligan et al. (2018) proposed (from a 60 year study of muirburn in blanket bog) that burning every c20 years resulted in highest species diversity, manageable fuel load, and good regeneration of *Calluna* stems. Glaves et al. (2013) reported that shorter rotation burns tended to favour single dominant species (*Calluna*/grasses on drier soils; cotton grass/*Molinia* on peatlands), but also found moderate evidence for *Calluna* benefiting more from longer rotation burns than shorter in peatland areas. Lee et al. (2013) found differential effects of burning rotation not just on different species, but also different effects on regrowth as opposed to seed bank within the same species. Other studies have proposed more diverse rotational lengths for other ecosystem effects such as reducing carbon loss (e.g. Santana et al. 2016 – see Chapman et al. (2017) review). Given the importance of fire frequency in determining species responses, it is important to address the question of whether there have been any major changes in frequency of muirburns in Scotland over time – despite its importance, there have been few studies to date attempting to quantify this as it is highly challenging and time-intensive to do so. The most recent published data comes from Douglas et al (2015) who reported (from remote sensing data) that frequencies of muirburn in Scotland increased by about 11% p.a. between 2001-2011. This is a very useful first attempt to quantify changes at a country level, but there are relatively few data points on their temporal change graph and several associated uncertainties with the spatial data and interpretation (see discussion on this in Brown et al. 2016, Davies et al. 2016b, c, Douglas et al. 2016). Earlier work by Hester & Sydes (1992) found reductions in burning frequency and scale between the 1940s-1980s (aerial photographic analysis within two moorland areas of Scotland where management for grouse was the dominant land use). More work is needed on this important question, to inform decision-making about management guidelines for muirburn into the future.

5.4 Impacts on biodiversity

Most papers indicate that the major determinant of any increases in biodiversity (plant or animal) is the mosaic of different ages of burn giving a mix of habitat, but also post-fire areas of bare ground/ash giving 'good substrates' for germination (e.g. Glaves et al. 2013). Clearly, in moorland areas that are naturally structurally diverse (e.g. with varied topography, lithography, mixtures of wet pools and drier ground), there are likely to be few potential structural-diversity 'benefits' of muirburn. Impacts on soil seedbanks are strongly dependent on whether or not the fire has burnt into the moss/litter/upper soil layers. Kelly et al. (2016), for example, found reductions in seedbank and vegetation diversity following wildfires in previously unburnt areas, probably reflecting the effects of greater fire severity of the wildfires as compared to controlled muirburn. It is also important to note that most assessments of longer-term impacts of muirburn come from chronosequence studies (i.e. space-for-time substitution: using different locations that have been burnt at different times prior to the study, which gives some well-known cautions for interpretation of results, such as assumptions of comparability of areas burned in different years under different weather and other conditions; assumptions that all sites

were comparable pre-burning, etc). A notable exception to this is the long-term (60 years) experimental study of muirburn effects at Moor House in northern England, an area of wet heath/blanket bog (see Milligan et al. 2018; Marrs et al. 2018 for most recent papers).

We found no direct studies on impacts of muirburn on below-ground biodiversity, apart from seed bank studies. Below-ground diversity plays a key role in regulating a whole suite of ecosystem functions (see later section), so the lack of information on muirburn impacts is a major knowledge gap. Fire intensity is again likely to be a key issue: impacts on soil structure/properties (and carbon in particular) have been shown to be more severe (sometimes catastrophic) under more intense, longer duration fires igniting dry soil/peat. Fires penetrating the moss/litter soil are likely to destroy much of the seed bank, which could result in a very different post-fire plant species composition post-fire (comprising vegetative regrowth and germination from seeds arriving in the seed rain as opposed to germinating from the soil seedbank). If the fire does not penetrate the moss/litter layer then we would expect below-ground biodiversity impacts to be much reduced, but there are too few data to support or refute this suggestion.

5.4.1 Heather (*Calluna vulgaris*)

There have been many decades of research on muirburn and heather, particularly by Charles Gimingham and his numerous research students (and subsequently their research students). It is widely considered that *Calluna* is fire-adapted and several studies have shown smoke-induced germination of this species. Data from Vandvik et al. (2014) in Norwegian heaths indicate that this trait is indeed an adaptation to long histories of fire; they found smoke-induced germination of *Calluna* in plants from traditionally burnt coastal heathlands, but this trait was lacking in *Calluna* plants from habitats with infrequent fires (Vandvik et al 2014).

There is strong evidence for muirburn carried out as per the Muirburn Code (2017) being capable of maintaining a heather-dominated habitat (e.g. Thompson et al. 1995), with a diversity of structure (from rotational burning of different areas) and relatively high associated plant species diversity (minus fire-intolerant species, some of which are of conservation concern in the UK, for example juniper), although much of the evidence for this is hard to unravel from other interacting influences such as grazing, as discussed below (e.g. Worrall et al. 2011).

Fire can have detrimental effects on heather under some conditions. For example, *Calluna* recovery is normally through regrowth from burnt stems, but this type of regrowth reduces with increasing age of heather above c15 years old (Miller & Miles 1970). Burning very old heather can result in the only regeneration being from seed – regrowth from seed is much slower and can lead to vegetation change away from *Calluna*-dominance towards e.g. grasses which establish faster after fire and tend to be more competitive than heather seedlings. Burning followed by heavy grazing can also be highly detrimental to post-fire heather recovery (see grazing section), again leading to change towards grass-dominance (e.g. Milligan et al. 2018). Stevenson & Rhodes (2000) found some paleoenvironmental evidence for burning causing long term declines in cover of heather in two out of 7 sites studied across the UK, but nationally there was no single causative factor for the declines in heather recorded.

5.4.2 Other vascular plant species

Reviews (e.g. Stewart et al. 2004, Towers et al 2010) found no significant overall effects of muirburn on plant species richness or diversity, but there was evidence for a general decline in diversity with increasing age of heather at burning (but considerable differences between studies). There is no consistent evidence for increases or decreases in biotic homogeneity following regular burning (e.g. Velle et al. 2014, Milligan et al. 2018; Marrs et al. 2018). A palynological analysis of fire history and vegetation composition over five millenia (Fyfe et al. 2018) also showed directionally different fire-vegetation impacts across different sites (all within Exmoor). Towers et al. (2010) found some evidence in the literature that burning on blanket bog was more likely to reduce plant species diversity than in drier heath, but this is not supported by the findings from the long-term study of blanket bog at Moor

House, which documented positive relationships between burning and diversity of vascular plants (Milligan et al. 2018), as did several other studies that they referenced – they hypothesised that the most likely causal factors were increased light and good substrate for germination following fire.

One of the aims of fire as a management tool on moorlands is to prevent regeneration of woodland and scrub and it is widely accepted that regular burning generally has detrimental effects on these taller woody species (including juniper: Thomas et al. 2007). There is very piecemeal evidence for impacts on other individual plant species (e.g. Glaves et al. 2013). Some studies, for example, found increases in cloudberry and cotton grass in peatland following regular burning (Glaves et al. 2013, Milligan et al. 2018). Milligan et al. (2018) found no evidence for deleterious effects of prescribed burning on peat-forming species (*Eriophorum*, *Sphagnum*) over 60 years, in fact the opposite: these species became more abundant in frequently burned plots than unburned. However, across a sample of 95 peatland sites across UK, Noble et al. (2018) found less *Eriophorum vaginatum* in burnt than in unburnt plots.

5.4.3 Bryophytes and lichens

With respect to Mosses, *Sphagnum* has been the main focus of most studies on muirburn impacts on bryophytes, as it is a key peat-forming species and its presence will promote carbon sequestration (see Chapman et al. 2017). There is still active debate about whether or not burning is detrimental to this species, as different studies have shown both positive and negative effects of muirburn – again we hypothesise that some of these differences will relate to differences in fire severity in different study areas. For example, Grau-Andrés et al. (2017) showed good regeneration after 22 months following experimental fires in a raised bog area in Scotland; and Davies et al. (2016b) quoted three different studies where *Sphagnum* had regenerated even after severe fires. But Noble et al. (2018) found lower abundance of *Sphagnum* in burnt sites as compared to unburnt. One of the longest running (60 years) experimental studies of muirburn impacts on wet heath/blanket bog (Milligan et al. 2018; Marrs et al. 2018) found greatest abundance of *Sphagnum* under most frequent (10-year interval) burning. There is also some evidence that changes in light and hydrology after heather-burning favour *Sphagnum* over some other moss species (Davies et al. 2016b, Chapman et al. 2017). Lee et al. (2013) found differential effects of fire rotation length on *Sphagnum* propagule abundance in the peat as opposed to regrowth, once again highlighting the differential responses not just between species but also within different growth stages of the same species. It has been suggested that different *Sphagnum* species may respond differently to fire (Davies et al. 2016b, Grau-Andrés et al. 2017), and since *Sphagnum* is not always identified to species level, this might be another reason for some of the ‘contrasting’ findings in different studies. Different responses of *Sphagnum* species to different specific elements of muirburn effects have also been experimentally demonstrated (Noble et al. 2017), with the two studied *Sphagnum* species both responding positively to ash deposition, but one of those species also responding (negatively) to post-fire-associated increases in peat bulk density.

Studies (of which there are few) show mixed effects of muirburn on lichen diversity depending on time since burning. Over the 60-year duration of their moorland experiment, Milligan et al. (2018) found greatest lichen diversity in sites burned every ten years, as compared to burning at longer durations or no burning. Davies & Legg (2008) (chronosequence study comparing fire sites from different dates) also found that peak lichen diversity tended to be 10-15 years after fire and declined thereafter, probably relating to increasing density of heather canopy. They did, however, find some differences between wet and dry heaths, with some replacement of lichens by mosses in burnt wet heaths. Once again, the positive biodiversity impact of a mosaic of different ages of post-burn sites was apparent – the authors found greatest lichen diversity in areas with a patchwork of different ages of burn. The differences in impact for different lichen species was also once again apparent, with some species associated most with old or unburnt stands (indicating that frequent burning would negatively impact these species). Lichen diversity in unburnt sites was hugely variable, indicating the importance of other site factors (including density of heather canopy) than just fire.

5.4.4 *Vertebrates*

As above, rotational muirburn provides a supply of young, nutritious heather shoots, so controlled rotational muirburn is generally considered beneficial for nutrition of vertebrates that consume heather (this includes domestic sheep, red deer and mountain hares in particular) and is widely used for management for sheep and deer. Mountain hares are already covered elsewhere in this review. Many other wild mammals use moorlands but not exclusively, and for many species the indirect effects of muirburn are probably more important than direct (assuming adherence to the Muirburn Code) in terms of impact on their prey species. The Muirburn Code (2017) contains regulations about minimum distances from otter holts, badger setts, water vole burrows, pine marten or wildcat dens, for example, to minimise direct detrimental effects of muirburn on these species.

Most research on muirburn impacts on vertebrates relates to birds and here is a summary of main impacts. Muirburn methods have been fine-tuned over many decades to 'best' suit the needs of grouse (e.g. Miller 1980) – young heather shoots are much more nutritious; grouse respond well to a mix of small patches of young nutritious heather for food and taller heather for cover (see also more recent work by Robertson et al. (2017)). It has long been established that burning larger areas is not generally beneficial for grouse (although fine for sheep and deer) and this was again demonstrated in recent work by Douglas et al. (2017) where they documented declines in grouse in large burn areas over a 14 year period. There is good evidence for positive effects of muirburn (in terms of maintaining open moorland, with mosaics of heather of different ages) on a number of ground-nesting birds, particularly waders (Thompson et al. 1995, Pearce-Higgins & Grant 2006, Thompson et al. 2016, Buchanan et al. 2017). A key interrelated issue here is also that in areas regularly burnt for grouse, predator control is also carried out and this has beneficial effects on a number of bird species (Buchanan et al. 2017, Mustin et al. 2018), particularly ground-nesting birds. The review by Mustin et al. (2018) gives a good summary of the overall mixed effects of muirburn on birds, with some positive and some negative for different bird species. For example, species showing negative associations with heather dominance/muirburn and more abundant in more grassy heaths include meadow pipits (Tharme et al. 2001) and skylarks (Pearce-Higgins & Grant 2006). Presence/absence of areas of tall heather (cover) is very important for several species (e.g. Pearce-Higgins & Grant 2006, Thompson et al. 2016). Again we see in several studies how different moorland management interacts to drive changes in moorland bird numbers (e.g. Calladine et al. 2014, Newey et al. 2016b, Douglas et al. 2017). Both these groups of authors and Buchanan et al. (2017) also stressed the benefits of vegetation heterogeneity in increasing bird diversity (as with all the other species groups we are examining here), reflecting the different needs of different species.

5.4.5 *Invertebrates*

There have been few studies on the direct impacts of muirburn, but several studies show indirect evidence for effects on invertebrates (see Usher & Thompson 1993, Towers et al. 2010, Graves et al. 2013, Davies & Legg 2016). The most consistent finding has been a positive association between rotational strip-muirburn and invertebrate diversity in general terms (but not immediately post-fire); this was presumed not to be due to muirburn impacts directly, but to the positive relationship between invertebrate diversity and the complex mosaic of open ground and taller heather created by regular burning of different patches. However, as with the impacts on vascular plants, this is not the case for all individual species, with some species groups showing declines in response to muirburn and others increases. Graves et al. (2013) and Mustin et al. (2018) give detailed reviews of some measured effects on different invertebrate groups. Eyre et al. (2003), for example, found positive effects of burning/cutting on habitat diversity for ground beetles and plant bugs but little effect on rove beetles and spiders. Some nationally rare species are associated with open conditions of recently burnt or cut heathland, but others with taller unburnt heather (e.g. Usher 1992, Usher & Thompson 1993, Eyre et al. 2003). We found no specific studies of muirburn impacts on below-ground invertebrate biodiversity.

5.5 Biodiversity impacts of burning vs. not burning, or muirburn vs. wildfire

It was traditionally thought that regular muirburn was necessary for *Calluna* to remain dominant, but this has been disproved at least for some moorland areas where heather remained dominant (through stem layering/rooting) for at least 40–60 years without burning (MacDonald et al. (1995) study of moorland areas not burnt since at least the 1940s from aerial photographs). Milligan et al. (2018) also refuted this. They demonstrated experimentally that *Calluna* increased in dominance over 60 years in unburnt wet heath/blanket bog plots more than in frequently burnt plots. It is not known what proportion of Scotland's moorland has never been burnt, so in the absence of more research we have no idea what proportion of heather-dominated moorland could retain heather dominance in the absence of fire. Related to this question, although much moorland is within the natural forest zone, given the very low remaining cover of forest and woodland in Scotland (<20%), rapid (re)colonisation by trees is unlikely in moorland areas that are far from tree seed sources.

We found almost no comparative information on impacts of heather burning versus cutting. The Muirburn Code 2017 Supplementary Information 1 gives a useful impacts comparison table, but no information on what is supported by research findings and what is expert opinion, so we cannot assess the strength of any evidence underlying this table. SNH (1996) Information Advisory Note on cutting (only 4 papers are given as 'further reading') reported that old heather stands regenerate much better after fire than cutting (as seedling regeneration is better). For younger heather, there is some evidence that more stems resprout after cutting than burning (40% more) so cutting may be better than burning when heather is young enough to resprout. General principles about biodiversity impacts are that cutting should be less detrimental than burning for much fauna and flora (and with cutting, a land manager can select to leave some species uncut, e.g. juniper), but species regenerating largely by seed should benefit more from burning (of course this is as long as it is not a severe fire that destroys the soil seedbank and burns deep into the soil/peat).

Comparisons of impacts of wildfires versus controlled muirburns are relatively few in number and in our view the main cause of differences in impact on biodiversity will relate to the greater likelihood of an uncontrolled burn being more severe than a controlled muirburn (see introductory section on fire characteristics). Very few fire studies have included detailed measurements of fire severity linked through to impacts, particularly relating to wildfires as these are by nature unplanned and usually only measured after the event! Typically, wildfires happen in late spring and summer, which gives a higher likelihood of severe effects. Hotter, drier conditions give a greater likelihood of deep soil heating/peat ignition (e.g. Albertson et al. 2010), with a high risk of the peat becoming hydrophobic and the seed bank being destroyed, leading to increased runoff and difficulty in vegetation re-establishing. It has been variously stated that regular muirburn can reduce fuel load and therefore the risk of wildfire, but there is very little evidence to support or refute this (e.g. Sotherton et al. 2017). The findings of Milligan et al. (2018) do support this – they found big differences in dry litter build-up over 60 years in unburnt versus regularly burnt plots.

5.6 Interactive effects on biodiversity of muirburn and other factors

It is well established that grazing-fire interactions can dramatically change vegetation species composition (see also grazing section of this review). Heavy grazing immediately post-fire can favour regrowth of grasses at the expense of heather and other less grazing-tolerant species (e.g. Worrall et al 2011). Milligan et al. (2018) found significant negative relationships between sheep grazing and *Sphagnum*, *Eriophorum* and lichen abundance, which could reverse the effects on these species that were associated with regular burning. Noble et al. (2018) found similar effects across their large number of sampled sites.

There are some hypothesised interactions between burning, nitrogen deposition and vegetation composition (e.g. Yallop et al 2006, Noble et al. 2018), but few studies have explicitly measured this. One exception to this is an experimental study by Barker et al. (2004) who found interactive effects of moorland burning and nitrogen deposition, leading to greater regrowth of *Deschampsia flexuosa* than *Calluna* in post-burn areas with high nitrogen additions. Milligan et al. (2018) proposed that more

frequent burning should be more likely to negate some effects of cumulative N deposition. Linked to this, the interactive effects of muirburn and nitrogen deposition on invertebrates are well illustrated by the heather beetle example: regular burning can reduce the nitrogen content of *Calluna*, which can reduce the probability of subsequent heather beetle attack, for example in areas of high N deposition (and younger heather also recovers better from heather beetle attack than older heather). But there are few actual examples of how frequently this kind of interaction happens. Noble et al. (2018) found a negative relationship between N deposition and *Sphagnum* which appeared to be stronger in burnt sites. They also suggested that grazing/pollution interactions with burning can both lead to increases in the invasive moss *Campylopus introflexus*. Noble et al. (2017) highlighted another possible driver for increases in this moss species, relating to muirburn-competition interactions: its positive response to ash deposition potentially giving it a competitive advantage over *Sphagnum*, for example.

Climate and fire interact strongly (as above), and the risk of more severe/uncontrolled fires is predicted to increase in Scotland as the summers are predicted to become hotter and drier (see Met Office data online), with more frequent droughts which are predicted to increase fire risk more on dry heaths than peatlands (Grau-Andres et al. 2018). In terms of moisture, example estimates are that *Calluna* moisture levels need to be <60% for ignition; but peat can ignite at c.100% moisture (see Chapman et al. 2017). Davies & Legg (2016) used the Canadian Fire Weather Index system to explore the potential for assessing fire risk in Scotland also based on fuel moisture (as well as spread index). This type of work gives important first steps towards developing a fire risk system for use in Scotland which is likely to become increasingly important under future climate change. Muirburn – rainfall intensity interactions recorded by Holden et al (2015) indicate that post-fire overland (water) flow and possibly also erosion could also increase under future climate predictions of increased frequency of intense rainfall events.

There are also associations between muirburn and wildfire: some wildfires result from muirburns getting out of control; conversely, muirburn, cutting and grazing can all be used to reduce fuel load and thus reduce the likelihood or at least the severity (temperature) of wildfires. Data on proportions of wildfires starting as muirburn vary between sources, but all data found show considerable proportions (by number or area). Luxmoore (2015, 2016), for example, reported >50% of wildfires recorded by SFRS between 2009-2015 as starting from muirburns (using data requested directly from the Scottish Fire and Rescue Services, with their associated uncertainties of causal attribution). Worrall et al. (2010) quoted data from the Peak District in England showing 25% of wildfires starting as muirburn, amounting to c.50% of the total area burnt, though only a small proportion of fires could be attributed to a cause, suggesting this information is of little value. Questionnaire data from 13 estates in 2003 (Legg et al. 2006) showed that 9 out of 17 wildfires were reported by estates as being caused by escaped management fires. We found no data on temporal trends in wildfire causes apart from the SFRS data time series graph shown by Luxmoore (2015, 2016) - a more substantial temporal analysis could probably be done using a combination of annual data requested from the Scottish Fire and Rescue Services and/or individual estates that also collect such data. It is clearly important that the Muirburn Code and regulation updates relating to muirburn activities use best available evidence to minimise the chance of muirburn fires getting out of control (e.g. developing a formal fire danger rating system – Davies & Legg 2016). This includes explicitly taking into account predicted climate-related changes of strong relevance to muirburn intensity/severity. As above, muirburn and grazing and cutting can also play a role in reducing fuel loads and possibly reducing the incidence or at least severity (temperature) of wildfires - modelling work by Albertson et al. (2010) indicates the potential benefits of reductions in fuel loads on wildfire temperature, but there is a lack of data demonstrating how these different management actions can be combined to best effect.

6 Grazing

6.1 Summary

Grazing has long been a feature of most moorland areas and, with burning, is responsible for their open character and their characteristic biodiversity. However, too many grazers can result in a conversion of heather-dominated vegetation to grassland and too few, especially, if there is no burning, can result in the invasion of scrub and woodland. However, as the grazers are often both domestic and wild then *management of one group can have indirect effects on biodiversity*. For instance, reduction/removal of livestock leaves more resources available for deer; but as deer forage more on heather than do sheep, the reduction in sheep grazing could mean higher grazing impacts on heather.

There are a number of evidence gaps with regard to grazing management of grouse moors and other moorland. In particular *our knowledge of the long-term impacts of grazing and burning is limited to one experiment* in Northern England – Moor House - so we have little knowledge of how impacts might differ in different contexts. We also know little about the short-term *impacts of grazing on heather regeneration and how grazing can help or hinder grouse moor management*, and in particular the impact of grazing on the length of required burning cycles. Finally, we know very little about *how grouse moor managers decide* whether management for grouse is their main focus, or whether management is for multiple objectives including livestock rearing and deer hunting.

6.2 Introduction

Grouse moors are usually dominated by heather (*Calluna vulgaris*) and species of similar growth form such as heaths (*Erica cinerea* and *E. tetralix*), crowberry (*Empetrum nigrum*) and blaeberry (*Vaccinium myrtillus*). These dwarf shrubs often occur in a patchwork with grasses ranging from bents (*Agrostis* spp.) and fescue (*Festuca ovina*) on “better” ground to mat-grass (*Nardus stricta*) and purple-moor grass (*Molinia caerulea*) on less productive areas.

The dwarf shrubs, exemplified by heather, are relatively unpreferred in the diet of grazers compared to the better nutrition provided by the grasses, especially by the bents and fescues (Gordon 1989). For a given density of grazers, the amount of grazing on the dwarf shrub component of the vegetation depends upon the relative abundance, productivity and nutritional quality of the dwarf shrubs versus the grasses (Milne 1991) as well as their spatial arrangement. For both sheep and deer, grazing on heather is higher adjacent to patches of grass (Hester & Baillie 1998) and in areas where there is more grass locally (Moore et al. 2015) as the grazing impact spills over from the attractive grassy habitats.

Dwarf shrubs are, however, more sensitive to grazing than grasses and grazing above a threshold can quickly lead to the replacement of dwarf shrubs by grasses; the best estimate for this threshold is c.30 % of the current year’s growth (offtake, Pakeman & Nolan 2009). Setting herbivore densities to prevent the replacement of heather by grasses requires adaptive management based on these offtake levels, as setting stocking levels based on the areas of heather and grasses, their productivity, nutritional quality and spatial arrangement is problematic. However, grazing below this threshold in conjunction with rotational burning can prevent the succession of moorland to scrub or woodland (Hobbs & Gimingham 1987).

Moorland areas have a long history of grazing but, given their sensitivity to too much or too little grazing, current heather-dominated moorlands have likely received enough grazing over recent times to prevent succession to scrub or woodland but not enough to favour their conversion to acid grassland communities dominated by species such as mat-grass and purple-moor grass. Their biodiversity value (and value in terms of delivering other cultural services, as discussed elsewhere) stems from their maintenance as open communities by grazing and burning. Species such as red grouse and stonechat (*Saxicola torquata*) favour areas with relatively complete heather cover (Pearce-Higgins & Grant 2006). Their value as habitats is recognised by the many areas of moorland designated as protected sites for their rich invertebrate and vertebrate faunas (Ratcliffe & Thompson 1988).

6.3 The impact of reduced grazing or its removal

There is no information on how driven grouse moor management affects herbivore numbers or even how many estates are managing for multiple objectives (grouse, livestock, deer). In general, the removal or reduction of grazing tends to benefit the dwarf-shrub species in the community at the expense of grasses (e.g. Hulme et al. 1999, 2002, Pakeman & Nolan 2009). Ultimately, grazing removal will result in the invasion of taller, woody species such as birch (*Betula* spp.) and rowan (*Sorbus aucuparia*) if local seed sources are close enough to allow dispersal. It can also benefit the spread of less desirable species such as bracken (Marrs et al. 2000). Woodland or scrub development necessarily would result in a significant shift in the species present; the desirability of such a change depends upon local context.

Where there is no tree or scrub invasion, a reduction in grazing has a wide range of impacts on biodiversity. This means a shift towards the more grazing intolerant species such as heather (Pakeman & Nolan 2009) and an increase in the species associated with them (Littlewood et al. 2006). Grazing removal can also increase the numbers of invertebrates (Baines 1996) and black grouse (*Tetrao tetrix*) performance is better on lightly grazed moors as a consequence. However, a reduction in grazing can also affect species that require more open areas for feeding, notably many wading birds (Pearce-Higgins & Grant 1996), especially golden plover (*Pluvialis apricaria*), and northern wheatear (*Oenanthe oenanthe*, Douglas et al. 2017). In general, grazing reduction leads to taller vegetation that shades out lower-growing species such as lichens (Lee et al. 2013; Milligan et al. 2018). Grassy areas on moorlands could also see a build-up of tussock forming species that can exclude other plant species (Hill et al. 1992) and reduce the availability of food for birds such as meadow pipits (Evans et al. 2015). As herbivory removes plant material, a reduction in grazing could lead to a need to burn more frequently to maintain areas of short heather (Davies et al. 2010a; van der Wal et al. 2011; see also the section on Muirburn impacts).

The above focus on the impacts of removing grazers covers both livestock and deer. However, as livestock and deer are in competition for food (Osborne 1984), a reduction in numbers of one will affect the other. For instance, if sheep are removed, then more resources are available for deer and their number would increase as their populations are limited by winter food supply (Clutton-Brock et al. 1987), unless increased culling took place. Whilst sheep and deer both show preferences for high quality forage like bent-fescue grasslands, their foraging behaviour is different due to differences in bite size and metabolic requirements (Illius & Gordon 1987). A switch from sheep- to deer-dominated grazing would have an impact on the vegetation as deer forage more on heather, and other dwarf shrubs, than do sheep (Cuartas et al. 2000); the same level of overall offtake would mean a greater impact on heather (DeGabriel et al. 2011). The latter paper concludes that the absence of sheep across large areas of the Scottish uplands could have detrimental impacts on both plant diversity and the maintenance of heather-dominated habitats, potentially as sheep prevent the build-up of rank, coarse grasses. The removal of deer from a livestock grazed moor would have less impact on the behaviour of the sheep as sheep already highly prefer to graze on grassy areas, although this reduction in deer numbers would reduce the impact on the heather. The overall impact would depend on management decisions about stocking rates.

6.4 The impact of increased grazing and mob stocking (tick mops)

Increased grazing would shift the balance between grasses and heather in favour of the grasses. This would be more evident if the increase in offtake stemmed from increased deer numbers as they concentrate more of their grazing on heather (Cuartas et al. 2000). However, if sheep are stocked to the point where they have to shift to eating heather, then the same overgrazing is seen. Overgrazing in this manner also has impacts on the rest of the system. For instance, it would shift the bird communities to ones dominated by grassland birds. For instance, meadow pipits (*Anthus pratensis*) favour intermediate covers of heather (c. 30 %), and skylark (*Aluada arvensis*) densities are higher on short grass moorland. Excessive grazing of heather would also reduce the food resource available for grouse.

To reduce the tick burden for grouse, sheep flocks are stocked at relatively high density (mob stocking) to act as “tick mops”. The sheep have been vaccinated and dipped so that ticks biting them are killed, reducing tick numbers in the present season and subsequent seasons as fewer ticks are available to reproduce (Fletcher & Baines 2018; Porter et al. 2011). However, this strategy is less effective if alternative tick hosts such as deer are present in significant numbers and is dependent on frequent treatment of the sheep with acaricides (Gilbert 2016). Hare numbers appear to have little effect on the incidence of tick-borne diseases in grouse (Harrison et al. 2010).

The impact of this method of tick control on biodiversity depends on the density of sheep and the range and quality of the habitats present for their grazing. If numbers are sufficiently high to force the sheep to forage on the heather above the threshold where damage can occur, then mob stocking could lead to a replacement of heather-dominated vegetation by that dominated by grasses (Pakeman & Nolan 2009) and thus impact on the sustainability of the moor as a grouse moor. Heavy grazing can facilitate the spread of mat grass (Grant et al. 1996), especially on low fertility soils (Hulme et al. 1999). Also, heavy grazing can reduce carabid beetles associated with shady, vegetated ground and reduce carabid species richness (Gardner et al. 1997). However, despite the potential impacts, there appear to be no published studies of the grazing impacts of tick control through the deployment of sheep as tick mops.

6.5 Interactions between grazing and burning

Most studies on the relationships between grazing and biodiversity have focused on how species differ in density or occurrence between different vegetation types or in response to changes in grazing. In contrast little has been studied concerning how grazing and grouse moor management practices, such as burning, interact to affect biodiversity. One exception to this is the study by Milligan et al. (2018) who examined the interaction between grazing and burning at Moorhouse, northern England, in a 60-year experiment. Both burning and grazing shift the vegetation away from one dominated by heather to one dominated by cotton grass (*Eriophorum angustifolium* and *vaginatum*). This shift was greater in the plots where burning and grazing were imposed together (significant treatment interaction). Both the short and long rotation burning treatments benefited *Sphagnum*, but the increase was slower under grazing. Grazing is also concentrated on areas that have been recently burnt, as the animals are attracted to the higher quality forage offered by young heather compared to the more woody, older heather (Grant 1968).

There is evidence from other systems, sagebrush steppe of North America (Davies et al. 2010b) and a range of habitats in Tasmania (Kirkpatrick et al. 2011), that grazing reduces the fuel load and that wildfires in moderately grazed rangelands have decreased severity and burn smaller areas for shorter periods. It is not known if the same applies to Scotland’s moorlands, but as burn characteristics are determined by the fuel load (Davies et al. 2009), this might be the case.

6.6 Grazing as an alternative land use

A shift away from management for grouse towards grazing as the main aim of land management would be biophysically possible on all existing grouse moors. The biodiversity impacts of this could be significant, if slow to appear. Firstly, there would be a shift from the small-scale patchwork burning necessary for grouse management towards larger, but less frequent burns to enhance the grazing quality of the heather. This could affect bird species that forage in more open areas such as waders (Pearce-Higgins & Grant 1996) as well as the invertebrates associated with more open areas produced by burning (Usher 1992). There would also be a reduction in legal predator control, which could result in reduced populations of a number of upland bird species, including lapwing (*Vanellus vanellus*), curlew (*Numenius arquata*), golden plover and red grouse (Fletcher et al. 2010; Douglas et al. 2014). As well as species loss there may be changes in diversity at larger spatial scales: a large-scale study of bird communities across the Highlands concluded that biodiversity was enhanced through maintaining heterogeneity in land management (Newey et al. 2016b).

7 Ecosystem services

7.1 Summary

The main ecosystem services delivered by areas managed for driven grouse shooting include some provisioning services (e.g. food and fibre provision), regulating services (e.g. carbon sequestration), and cultural services (e.g. outdoor recreation, field sports). The Natural Capital Asset Index indicates that service delivery potential in moorland has been declining since 2000, albeit with recent increases.

Different upland habitats provide different types and levels of ecosystem service delivery. Areas managed for driven grouse shooting may contain several different habitat types, but the habitat type of most direct relevance to driven grouse shooting is dwarf shrub heath. However, it is *sometimes not possible to attribute levels of service delivery to specific habitats* within the uplands; studies often assess service provision over large areas (e.g. service delivery by catchments) without attempting to attribute relative service delivery levels to specific habitats within those areas.

Where habitat-level attribution is possible, dwarf shrub heaths are often considered of relatively high importance, but *very few studies explicitly examine the delivery of services by areas managed for driven grouse shooting*. Furthermore, studies of service delivery by uplands or moorlands *commonly focus on a small subset of services*; information on the delivery of many services – particularly cultural ecosystem services – is lacking.

Taking the term ‘biodiversity’ to mean ‘nature’, some of the key ecosystem services and benefits from moorland systems, including those managed for driven grouse shooting, are clearly underpinned by their biodiversity. These include, for example, the provision of meat from grazing animals and grouse and deer for recreational hunting. For other services the relationship is much less clear. This is in part because of the lack of clarity concerning the attribution of service delivery to specific habitats, or to areas that are or are not managed for driven grouse shooting.

Another factor adding complexity to the biodiversity-benefits relationship is the role of people in co-producing ecosystem services. Because of the *critical role of the interactions between people and nature* in delivering some services, ecosystem service delivery can vary depending on the accessibility of land. Overall, we need to develop a better understanding not only of the flows of ecosystem services from areas of land managed for driven grouse shooting, but also *how ecosystem service potential is converted into benefits*, and when co-production is a key part of this process.

If we consider how key management actions strongly associated with driven grouse shooting influence service delivery, targeted control of particular species (i.e. predators and hares) will have complex effects propagated through networks of interactions with other species and mediated through interactions between people and the environment. We suggest that the effects of these management actions will be relatively localised and to some extent dependent on distances to areas with large numbers of people. Overall, we can see that the response of wider ecosystem services to muirburn is *complex and likely also to be highly context dependent*, varying both with biophysical factors (e.g. vegetation types, climate) and human population densities (altering, for example, risks of wildfire). Grazing influences both locally-delivered services (e.g. meat, recreational hunting) but also some of the more dispersed benefits such as climate regulation and pollution mitigation. It also interacts with other management activities – such as muirburn – to regulate services provision.

Overall we lack information in particular on the complex relationships between nature, people and the delivery of benefits from areas of land managed for driven grouse shooting, and the impacts of management for driven grouse on the delivery of these services. Given that dwarf shrub heath habitats are considered important for ecosystem service delivery in the uplands, it seems clear that we need to bring these issues together in new studies aiming explicitly to understand how management for driven grouse shooting affects ecosystem services and delivery of benefits to people.

7.2 Introduction

Here we consider the links between biodiversity and ecosystem service provision in areas managed for driven grouse shooting in Scotland, and how the impacts of management strongly associated with driven grouse shooting might affect ecosystem service delivery.

Ecosystem service concepts are rapidly evolving, and various frameworks have been developed for classifying ecosystem services and for explaining their relationships to the benefits which people derive from the environment. This section of our review takes as a starting point the work by Van der Wal et al. (2011) in the UK National Ecosystem Assessment, and so we use the conceptual framework and terminology used in UK NEA 2011 publications, noting that these initial conceptual frameworks were updated in more recent UK NEA follow-on work (UK NEA 2014). It is also worth noting that UK NEA ecosystem service classification does not follow the now widely-used CICES classification. However, as the UK NEA provides one of the most detailed accounts of service provision in upland systems, we have chosen to build on it here. Although terminology may differ, we feel that key messages remain consistent. Wider and detailed overviews of conceptual frameworks can be found in, for example, Potschin et al. (2016).

Overall, we take ecosystem services as being “the outputs from ecosystems from which people derive benefit” (Mace et al. 2011). These include intermediate services or ecosystem processes (also called supporting services) such as soil formation, and nutrient and water cycling, and final ecosystem services (including provisioning, regulating and cultural services) from which we derive goods and benefits directly.

7.3 What ecosystem services do areas managed for driven grouse shooting provide?

In their contribution to the UK National Ecosystem Assessment, Van der Wal et al. (2011) consider the balance of ecosystem services delivered by the UK’s mountains, moorlands and heath (MMH) habitats. This covers a number of habitat types including bracken-dominated habitats, dwarf shrub heaths, upland fen, marsh and swamp, bog, montane habitats and inland rock. Whilst areas managed for driven grouse shooting may contain elements of several of these habitat types, the habitat type of most direct relevance to driven grouse shooting is clearly dwarf shrub heath. In their Table 5.5 (p. 136), Van der Wal et al. detail the main goods and benefits derived from MMH habitats. Some goods and benefits are delivered by several MMH habitats, but for the purposes of this review the results of their assessment for dwarf shrub heaths are summarised in Table 2.

Van der Wal et al. (2011) indicate that the attribution of the relative role of different MMH habitats in delivering some services is hard to assess. This applies, for example, to *Potential for flood risk mitigation* or *Freshwater provision for domestic and industrial use*. In these cases, services are provided by wider upland areas that contain mosaics of a range of habitats. However, where contribution can be quantified relative to other MMH broad habitats, dwarf shrub heaths are considered of high importance for delivering multiple provisioning services (*Food provision, Fibre from wool, Traditional lifestyle products, Opportunity for wind energy schemes*), regulating services (*Carbon sequestration, Opportunities for wildfire risk mitigation*) and cultural services (*Landscape as symbols of a popular national identity, Outdoor active tourism and recreational opportunities, Field sports, Opportunities to learn about the natural world and cultural heritage*). Of the 22 services where a habitat-level attribution of importance is possible, dwarf shrub heaths were considered the most or joint most important of the MMH habitats for delivering 14 of these services (indicated in Table 2). However, it is important to point out that this assessment of a strong relative role for heathlands is to some extent at odds with that provided by the Natural Capital Asset Index (NCAI), for example through its Ecosystem Service Potential scores. The NCAI assessment indicates that although temperate shrub heathlands are important service providers, of five key upland habitats (raised and blanket bogs; alpine and subalpine grassland; arctic alpine and subalpine scrub; temperate shrub heathland; montane) temperate shrub heathland have the highest or joint highest scores for only 9 out of 24 relevant services. Differences between these assessments may arise from variability in expert scoring approaches and/or differences in service classification systems.

Werritty et al. (2015) highlighted the role of moorland systems more widely in delivering a number of key ecosystem services including climate change regulation, flood control and the role of upland geodiversity in providing a platform for ecosystem service delivery. They also noted the relatively low ecosystem service delivery potential of Scotland's moorland as indicated by the Natural Capital Asset Index (NCAI). Werritty et al. used the 2012 version of the NCAI, and the NCAI has recently been updated following a comprehensive review of underpinning datasets (Albon et al. 2014). The revised NCAI³ indicates that heathland (now assessed separately from mires, bogs and fens) is no longer the worst performing habitat (this is now agricultural and cultivated land), but heathland still shows a decline in potential for service delivery since the NCAI's 2000 reference point, although recent years have shown a slight upturn, and heathland is the second worst performing habitat in the NCAI per spatial unit (after montane habitats).

The importance of location for trends in service delivery is demonstrated in a recent study by Dick et al. (2016), which considered changes in ecosystem service delivery across the 22 Environmental Change Network (ECN) sites. For three key moorland/upland sites (Snowdon, Cairngorms and Moor House), they found increases in cultural services (e.g. recreational and education activities) and regulating services (carbon storage) which did not match general trends for upland systems as summarised in the UK NEA. Dick et al. argued that this was because of the location of these sites within National Parks or reserves, which would promote their use for recreation or education and enhance the level of legislation-driven nature conservation activity being undertaken. In essence, delivery of ecosystem services is increasing because of increased service use, rather than increases in service potential. In terms of changes in potential, declines in the NCAI for heathlands have been driven by declines in upland bird populations and the status of designated natural features, although improvements in the latter have driven the recent increase in the NCAI.

We have looked for recent studies examining the role of biodiversity (in its widest sense) in delivering ecosystem services in moorland systems, and the possible impact of management activities strongly linked to driven grouse shooting on them. During this process it is notable that although many papers mention the role of moorland systems in delivering ecosystem services (e.g. Thompson et al. 2016) few look in detail at this biodiversity-service provision linkage, and the identified studies that attempt this commonly focus on a small subset of services, in particular carbon storage, wildfire risk mitigation, regulation of water flows and quality, and some aspects of cultural service provision. For example, the review of wider ecosystem effects of grouse moor management by Grant et al. (2012) focussed in particular on carbon fluxes and water provision. Our observation that there is a concentration of research on a small handful of services mirrors patterns found by other studies (critiqued in Eastwood et al. 2016) and may reflect the relative ease with which these services can be measured or valued, or their perceived importance. However, it is also clear that they do not cover the full spectrum of services identified as relevant to dwarf shrub heaths by studies such as Van der Wal et al. (2011) or by the NCAI. In addition, and as reflected in Table 2, some studies often do not or cannot directly attribute service delivery to heather moorland, and certainly not to areas managed specifically for driven grouse. In fact, and as highlighted by Werritty et al. (2015), we do not have a clear idea of the amount of land currently managed for driven grouse shooting, and so it is difficult to assess its role in service provision on a simple pro-rata basis, although the GIS/RS components of this study provides some information on whether this clear information gap can be rectified.

7.4 What regulates these ecosystem services?

7.4.1 *The role of biodiversity in regulating service delivery*

A problem with discussing the links between biodiversity and ecosystem services is that in different contexts the term 'biodiversity' is used to mean different things. Some research studies focus particularly on how the diversity (that is, the richness) of genes, species or habitats regulates ecosystem services (for example, see Hooper et al. (2005)). Alternatively 'biodiversity' is used as a way to refer to 'nature'; this is a common usage in nature conservation, for example in the Scottish

³ <https://www.nature.scot/scotlands-natural-capital-asset-index-0>

Biodiversity Strategy. Our literature review has taken this second usage, examining how management activities strongly associated with driven grouse impact on nature. Consequently, when considering how biodiversity underpins ecosystem service delivery in moorland systems, we're asking whether and how any components of nature underpin service delivery.

In some situations the links between biodiversity and service provision are clear. Grouse and hares feed on and live in heather moorland (see section 3), so the occurrence of heather directly underpins the delivery of field sports (grouse and hare shooting) and food provision from game. With respect to other provisioning services (e.g. food and fibre production from sheep and food provision from venison) grazing animals, such as cattle, deer and sheep, are similarly supported by the heather (see section 6). But grazers also forage on other habitats in upland mosaics and prefer grasses to heather. Consequently, livestock production and deer farming/hunting, though clearly and directly supported by biodiversity in moorlands, are less dependent on heather and more dependent simply on the occurrence of any suitable fodder species.

The biodiversity of moorland systems, including those managed for driven grouse shooting, also plays a clear role in delivering some cultural ecosystem services. Table 2 shows that some of the cultural benefits we derive from dwarf shrub heath are dependent on the occurrence of particular habitats or species. Delivery of the benefits from *Tourism and recreation based on wildlife watching*, for example, may be positively influenced by the occurrence of certain species, including grouse and mountain hare, or the species that predate them such as golden eagle.

For other services the links between the biodiversity found in moorland ecosystems and service delivery become less clear. As discussed above, although biodiversity can play a regulatory role it is often not stated, or not possible to state, exactly which components of biodiversity (which bits of nature) within a given upland area contribute to delivering a service. A key knowledge gap here is the role of genetic diversity. Although we can say with some certainty that particular species are important for some services (as detailed above) the long-term sustainability of service provision may be underpinned by their genetic diversity. The link between species genetic diversity and ecosystem function and services is a general ecological knowledge gap, and is certainly relevant to service provision in moorland ecosystems.

As an example of the problem of attributing service provision at the habitat level, and with respect to the flow of water, Capell et al. (2011) working in the North Esk catchment in Scotland, examined the role of upland systems in regulating run off throughout the year. They found that the uplands dominate winter high flow responses but are also important in the summer when small upland aquifers provide baseflow to dilute pollutant inputs in lowland areas. Such flow processes can be determined by the state of the vegetation: Grayson et al. (2010), in a study of a blanket-peat dominated catchment in northern England, found that restoration of the vegetation helped to smooth discharge rates from the catchment, easing the peaks of flow associated with rainfall events. Gao et al. (2016) used a modelling approach to assess how changes in vegetation in upland headwater peatland influenced flows. They found that the occurrence of *Sphagnum*-dominated regions adjacent to streams and rivers helped to reduce flow peaks compared to bare peat, thus aiding flood management. However, although demonstrating the role of upland systems – and the biodiversity within them – in service delivery, none of these studies directly assess the role of areas managed for driven grouse shooting, or the types of habitat commonly associated with driven grouse shooting (such as dwarf shrub heath). This is reflected in Table 2 where attribution of the role of different habitats for *Freshwater provision for domestic and industrial use* and *Potential for flood risk mitigation* is considered difficult.

7.4.2 *The role of people in delivering ecosystem service benefits*

Another factor complicating the link between biodiversity and service provision in moorland systems is the role of people. If we take as an example the role of heather moorlands in *Opportunities for wildfire risk mitigation*, people can have both beneficial impacts on delivery of this service (with muirburn reducing fuel load and hence fire intensity and carbon loss – see below) and negative impacts

(muirburn increasing the risk of fire ignition; see section 5). Fischer and Eastwood (2016) considered the role of humans in delivering ecosystem service flows, and argue that “Such flows are often not provided by the ecosystem on its own but through the interplay between people and place; without the involvement of skilled individuals and their equipment, an ecosystem structure – e.g., a tree or red deer – would not provide a flow of benefits, such as building material, food or enjoyment.”

The concept of co-production is particularly relevant for areas of land managed for driven grouse shooting, not least because of the wide number of cultural ecosystem services they deliver, which by definition are the product of the interaction between people and biodiversity/nature/the environment. The importance of UK moorland systems for cultural service delivery is emphasised in Table 2 with a relatively substantial role for dwarf shrub heaths in the delivery of cultural ecosystem services. Indeed, Scottish heather moorlands have been described as “the epitome of a cultural landscape” (Lindsay and Thorp 2011). However, Fischer and Eastwood (2016) emphasise that co-production and the role of the people in ES delivery is not confined to cultural services.

The potential for co-production can be strongly influenced by the accessibility of the land. The importance of access was emphasised in a study by Eastwood et al. (2016) looking at the impact of conservation management on service delivery at a range of locations and in a range of habitats across the UK. They found that when cultural service delivery was enhanced this was often because conservation management was associated with an investment in infrastructure such as paths and visitor facilities, and this finding may be reflected in the responses found in the study of ECN sites by Dick et al. (2016).

As many cultural services (and indeed many services overall) are not realised without direct interaction between people and an environment, it is not surprising that a critical factor influencing the delivery of cultural ecosystem services is the proximity of an area of land to human populations. For example, Schmidt et al. (2016) undertook a study contrasting the value for service provision of upland areas of the Pentlands compared to urban greenspace in Edinburgh. They emphasised “the substantial value of upland areas in close vicinity to a city for physically using and experiencing nature, with a strong acceptance of nature conservation”. Their study also indicates the importance of upland systems to a very wide range of people, especially if they are near to an urban centre.

It might be argued that even if an area of land is isolated, that land can still provide important services for people living in the vicinity. However, whilst still benefiting from services such as water provision and regulation, even for those people living close to the land there are not necessarily derived benefits from some ecosystem services, for example cultural service benefits. Mullin et al. (2018), in a study based in England, noted that the rural poor in upland areas suffer deprivation even though they are in close proximity to “extensive coverage of various higher quality NC [Natural Capital]”. They proposed that the equitable management of ecosystems should be driven at a local level. This message is reiterated by Clarke et al. (2015) in a study of ecosystem service provision in an upland catchment in northern England which notes the importance of involving local communities in land management decision making. It is also reiterated by Reed et al. (2017) when exploring options for a Payment for Ecosystem Services (PES) scheme associated with the Peatland Code; they state “Place based PES schemes can mitigate negative trade-offs between ecosystem services, more effectively include cultural ecosystem services and engage with and empower diverse stakeholders in scheme design and governance”. Mullin et al. (2018) suggest that to achieve this “the relationship between environmental benefits and deprivation should be assessed at this [local] level and analysis should move beyond NC to address the ecosystem services that flow from it.” To put it another way, we can’t assume that the occurrence of high-quality environments brings benefits to local communities – it is important to examine who benefits from ecosystem service flows, or indeed who may experience disbenefits from them. The issue is perhaps best summed up by Eastwood et al. (2016) in their study of ES delivery by protected areas; they note that “spatial and social context of a protected area or non-protected area is therefore critical in determining cultural service delivery and associated values”, and this is likely to be true for areas of land managed for driven grouse shooting.

In summary, for some ecosystem services it is clear how the biodiversity (in this context the nature) of moorland systems can underpin their ecosystem service delivery. But for many services the regulating role of biodiversity is not clear. This can be in part because it is hard to determine the relative extent to which a particular habitat in a larger region – for example moorland managed for driven grouse shooting within an upland catchment – contributes to service delivery. It can also be because the interplay between people and the environment is critical in regulating and delivering the services and benefits. Although some services and benefits can be exported from an area of land, and this includes some cultural service benefits such as existence value (as well as the more obvious provisioning and regulating services), for others proximity and access to land is a key factor regulating service provision. This highlights perhaps how ecosystem service thinking has moved on since publication of the original UK NEA in 2011. Notably ecosystem service potential, not delivery, is the factor being assessed by the NCAI. The scorings for goods and benefits from dwarf shrub heaths shown in Table 2 should also be taken as the *potential* for delivery of goods and benefits. Although many goods and benefits can be received at a distance, we should avoid assuming that they *are* delivered and need to recognise that the generation and delivery of some of these benefits is strongly regulated by the interplay between humans and nature.

7.5 What are the impacts on ecosystem services of management activities strongly associated with driven grouse shooting?

Here we consider how the four focal management actions strongly associated with driven grouse shooting (legal predator control, mountain hare management, grazing, and muirburn), impact on the delivery of ecosystem services and associated benefits. Unless otherwise stated the evidence base supporting this overview is provided in the four detailed review sections. With the exception of grazing, which happens in conjunction with - rather than because of - driven grouse shooting (with the exception of stocking animals as tick mops), these management practices are undertaken for the promotion of a mosaic of different ages of heather moorland to benefit grouse populations. The associated biodiversity responses (mediated by human-environment interactions) then clearly help to deliver a number of cultural and provisioning benefits (including *Cultural heritage and aesthetics, Tourism and recreation, Food provision – deer and game birds*). Consequently, and to save repetition, we focus here on the delivery of other services and benefits.

7.5.1 Legal predator control and mountain hare management

We suggest that both legal predator control and mountain hare management impact on service delivery in broadly similar ways, and that assessing some of these impacts is challenging for broadly similar reasons.

In both cases, on-the-ground management actions involve direct regulation of components of biodiversity: predators or mountain hares. Of themselves, reductions in populations of target species might be assumed to reduce delivery of some benefits, for example *Tourism and recreation based on watching wildlife*. However, the ultimate outcome for service delivery is moderated in two main ways. Firstly, there are wider biodiversity impacts which are propagated through interactions between target and other species. Legal predator control can have a range of effects on moorland bird species, leading to increased breeding success and numbers of some ground nesting birds, particularly upland waders, whilst leading to declines in others. Similarly, reductions in hare numbers may benefit plant species which are particularly susceptible to hare browsing (for example some tree species) whilst leading to declines in the populations of predators such as golden eagle for which hares can be important prey. Importantly these knock-on biodiversity effects can be unpredictable or unexpected. For example, removal of large predators might lead to increases in the abundance of smaller (non-target) predators, which in turn will have both positive and negative biodiversity effects, whilst reductions in hare numbers will likely not lead to reduced tick burdens or increased food availability for red grouse. Adding to this uncertainty are major knowledge gaps about how the regional context (i.e. the regional state of predator or hare populations) will influence the response of target species to management at a particular location.

The second factor moderating the response of service delivery to legal predator or mountain hare population control is the interactions between people and the environment. Whether increases or decreases of particular species are considered a benefit or disbenefit depends on who is asked (Van der Wal et al. 2011). It also depends on whether these changes in biodiversity are experienced; increases in the abundance of rare upland waders may deliver little in the way of cultural ecosystem services if they occur in isolation from the people that value them. It is difficult to predict the spatial scale of effects of legal predator or mountain hare control at a site, and populations of predators and hares in neighbouring areas may be affected by these management actions. However, we suggest the delivery of the services and benefits that are most strongly affected by mountain hare and legal predator control – for example some of the cultural services – is quite localised compared to some of the other services and benefits (which are less strongly affected, for example *Freshwater provision* or *Climate regulation*). Consequently, the spatial location of the sites where these management activities take place – for example their distance to high densities of population - is likely to be relatively important in determining the impacts of these management actions on service delivery.

7.5.2 Muirburn

The impacts of muirburn on ES delivery can be very substantial and wide-reaching. We have discussed differences in the impacts of muirburn and wildfire on biodiversity (Section 5), and the two processes clearly interact with respect to regulating ecosystem service provision. By reducing fuel load, muirburn may play an important role in delivering *Opportunities for wildfire risk mitigation*, and recent studies have explored the impact of muirburn on wildfire frequency and severity. For example, in a modelling study based on an area of moorland in the Peak District National Park, Albertson et al. (2010) found that controlled burning, grazing and mowing can all help reduce the build-up of fuel load and limit the temperature of wildfires. However, as discussed in the Muirburn section, out-of-control muirburn is itself a known source of varying proportions of wildfires as well. In addition, the occurrence of wildfire is strongly regulated by interactions between people and the environment. Under future climate change there is likely to be an increased risk of wildfires, particularly on dry heathlands, and particularly fires originating from recreation (Albertson et al. 2010). Consequently the threat from wildfire, and benefits from reducing the impacts of wildfires, are likely to be greater nearer to centres of population or areas with large visitor numbers.

Both muirburn and wildfire influence moorland's delivery of key regulating services, in particular *Climate regulation* through both *Carbon storage* and *Carbon sequestration potential*. Muirburn can have both positive and negative effects on *Carbon storage*, in part by directly altering the amount of carbon locked into a habitat's soil and vegetation, and in part by altering a habitats community composition and hence it's *Carbon storage potential*. There have been two substantial reviews of the impacts of muirburn on soil carbon and biodiversity (Towers et al. 2010) and on peatland and peat soils (Chapman et al. 2017), as well as a focus on the impacts of muirburn on carbon storage in previous reviews (e.g. Grant et al. 2012). To summarise, there is often an assumed net loss of CO₂ under normal muirburn, but the evidence is not conclusive. Following muirburn, CO₂ losses increase through plant and soil decomposition/respiration but fall as vegetation (and photosynthesis) recovers. Muirburn is not always detrimental to some of the most important carbon-fixing plant species (Davies et al. 2016d). Although burning may favour *Calluna*-dominated systems, and in some cases appears to be associated with a decline in *Sphagnum* and favouring of other moss species (Noble et al. 2017, 2018), Heinemeyer and Vallack (2015) argue that the relationship between *Calluna* and *Sphagnum* is not always antagonistic, and that heather can offer protection for *Sphagnum* growth, particularly in older stands of *Calluna*. Similarly Lee et al. (2013), in a study on Moor House NNR in northern England found "no evidence to suggest that prescribed burning was deleterious to the abundance of peat-forming species", and this message was repeated in an analysis of long-term data from multiple sites (Milligan et al. 2018) which showed an increase in abundance of peat forming species in frequently burned compared to unburned plots. A very recent study has shown that regular, rotational burning (10 year intervals) reduces carbon sequestration compared to unburnt areas of moorland, but that did not prevent soil carbon accumulation (Marrs et al. 2018).

Muirburn and wildfire can interact to regulate delivery of *Climate regulation* services in relation to impacts on carbon. Whilst muirburn reduces the amount of carbon stored in aboveground vegetation, it also reduces the likelihood of very substantial carbon losses due to wildfire (including burning of peat); the complexity of this interaction has been explored in some recent studies. Allen et al. (2013) found that controlled short-rotation burns may reduce aboveground carbon loss during wildfires. However, the relationship between muirburn frequency and carbon storage/loss is complex. Santana et al. (2016) found a complex trade-off when trying to optimise moorland burning rotations for present and future carbon emissions. The modelled optimum frequency of burn rotation was found to vary along a latitudinal gradient in the UK – being longer in northern locations - and also with projected frequency of wildfires. Again, this demonstrates that the role of moorland management in regulating ecosystem service delivery may be highly context dependent and influenced by future projections of climate change.

By influencing the chemical composition and particulate content of run-off from moorland systems, muirburn can clearly impact on *Pollution mitigation* and *Freshwater provision*. However, the data on muirburn impacts on dissolved organic carbon (DOC), particulate organic matter, suspended sediments, aluminium, iron etc in runoff are inconclusive, with varying data on losses and subsequent recovery within the system as vegetation regrows (Chapman et al. 2017; Holden et al. 2015; Davies et al. 2016a, b; Kelly et al. 2018). Again, it is likely that fire characteristics have a strong influence on findings, and there is also some evidence for interactive effects with historical and current pollutant deposition and post-fire rainfall patterns. There is very little data on muirburn and erosion. Severe fire that leads to physical changes in the peat is most likely to lead to erosion, although it has also been suggested that small scale erosion also occurs as a result of fire, although there seems to be no data on this. Time scale is also important – immediately post-fire there are likely to be pulses of DOC and other pulses in run-off but these can be very short-lived. Under ‘normal’ muirburn regimes (following the Muirburn Code) where the fire does not burn into the moss/litter, initial losses of carbon are generally replaced as the vegetation grows back – the rate of carbon sequestration is strongly affected by vegetation type, soil type and fertility.

The ecosystem service impacts of muirburn are potentially very wide-reaching, with some of the services delivering global goods (e.g. *Climate regulation*). However, the responses of ecosystem services to muirburn are clearly complex. The potential complexity of responses of ecosystem services to fire is illustrated well in a recent review by Harper et al. (2018); a clear example they provide is the varying results within the UK research literature of the impacts of prescribed burning on water chemistry, with different measures of water chemistry showing highly contrasting responses depending on the study (summarised in Harper et al. 2018, Table 3). Overall, we can see that the response of wider ecosystem services to muirburn is similarly complex and is also likely also to be highly context dependent, varying both with biophysical factors (e.g. vegetation types, climate) and human population densities (altering, for example, risks of wildfire).

7.5.3 Grazing

As for legal predator and mountain hare population control, the impacts of grazing management on service delivery can be both direct and indirect. Direct effects come obviously from the occurrence of grazing animals and the provisioning services they deliver. Grazing of moorland areas provides provisioning services in terms of meat from livestock and from deer, and to a much lesser extent, fibre (wool) and leather. Deer stalking also provides a recreation service.

A recent study of moorland rewilding (Ermgassen et al. 2018) explored changes in three ecosystem services - timber (provisioning service), pollination (regulating service) and aesthetics (cultural service) – in areas of moorland that were rewilding (increasing in native woodland cover) following substantial reductions in grazing pressure. They found that rewilding led to increased tree recruitment and woody biomass, and a linear increase in perceived aesthetic quality, but had no effect on pollination. However, and as discussed elsewhere, whether or not reductions in grazing will lead to changes in woodland cover will in part be regulated by distance to seed sources. And whether increased woodland cover is an aesthetic benefit will depend on the stakeholder group being surveyed.

As well as provisioning and cultural services, grazing can also impact on regulating services. With respect to *Pollution mitigation* and *Climate regulation*, excessive grazing can contribute to soil erosion (Evans et al. 2005) and the reduction of above-ground carbon stocks (Ward et al. 2007). However, these responses are not straightforward: flux measurements show enhanced CO₂ uptake under grazing but also higher CH₄ emissions (Ward et al. 2007). Medina-Roldan et al. (2012), working in an upland grassland system in northern England, found that grazing exclusion did not impact on soil carbon and nitrogen stocks, although it did lead to increased dwarf shrub cover. They noted that this lack of response in soil carbon stocks might be due to the short-term nature of their study, emphasising the need for long-term studies and monitoring. Changes in soil carbon in upland systems are slow and likely to be detected only in the long-term (Smith et al. 2014). Even after 30 years of grazing, changes in soil carbon have not been detected in some instances (Garnett et al. 2000). It appears that soil carbon build-up after grazing removal only occurs where nitrogen deposition is above a threshold (Smith et al. 2015).

Grazing management can also interact with other management activities to alter service delivery. The study by Milligan et al. (2018) examined the interaction between grazing and burning at Moorhouse, northern England, in a 60-year experiment. Both burning and grazing shifted the vegetation away from one dominated by heather to one dominated by cotton grass (*Eriophorum angustifolium* and *vaginatum*). This shift was greater in the plots where burning and grazing were imposed together (significant treatment interaction). Both the short and long rotation burning treatments benefited *Sphagnum* (with implications for carbon sequestration, as noted above), but the increase was slower under grazing. Ritson et al. (2016) found that having more productive plants on peatland systems leads to greater rates of decomposition and loss of DOC into the runoff. Grazing is often concentrated on areas that have been recently burnt, and higher levels of grazing can promote the occurrence of a more productive moorland flora (i.e. reduced heather and increased grass abundance) which in turn can lead to changes in soil processes and possibly also the quality of run-off. This is a good example of important grazing-fire interactive effects.

7.6 Summary of ecosystem service impacts

The above overview is not intended to be a comprehensive assessment of how these four management activities impact on the delivery of ecosystem services from moorland systems managed for driven grouse shooting. However, it does provide an indication of the responses of some of the key ecosystem services and associated benefits. It is clear that these responses are complex, context dependent, interactive, and that there is much that we don't know. At a basic level without management for driven grouse, and the rotational burning this entails, in Scotland we would not have the large expanses of 'cultural' (managed by fire) dwarf shrub heath and high population densities of grouse which contribute to the role of moorlands in delivering some ecosystem services (Table 2). A clear role of dwarf shrub heath (cultural and natural) is delivery of a wide range of cultural ecosystem services, and it is notable that whilst there have been studies on carbon storage, wildfire and grazing, in particular there is a dearth of data on how cultural services are provided and might be influenced by changes in grouse moor management. The response of cultural ecosystem services is complex and can be unpredictable, a point picked up by Werritty et al. (2015) with respect to the cultural ecosystem service changes that might be expected in response to re-wilding.

It is also hard to separate dwarf shrub heath's role from those of other upland habitats in delivering some services (Table 2), and for many services it is not possible to know how management for driven grouse effects service delivery. The overall paucity of our knowledge on the interactive effects of management activities was recently highlighted by Davies et al. (2016d). Finally, service delivery is highly dependent on the interactions of people and the environment. Management for driven grouse could promote or limit these interactions, and in a manner that differs between different stakeholder groups and spatial locations. There has been a historic focus on a small number of ecosystem services, a general lack of focus in such studies on service provision specifically from moors managed for driven grouse, a lack of focus on the role of particular components of biodiversity (for example genetic diversity), and recent development of new thinking on the generation of services by the interaction of

people and the environment. It seems clear that we need to bring these issues together in new studies aiming explicitly to understand how management for driven grouse shooting affects ecosystem service delivery.

Table 2: Main goods and benefits derived from dwarf shrub heaths. An indication is given, based on expert opinion, of the relative importance of dwarf shrub heath habitat for providing these goods and services using a four-step scale ranging from negligible (-) to high (+++); 0 indicates that attribution of relative service delivery to dwarf shrub heath habitat is difficult; * indicates that dwarf shrub heath is considered the most important, or joint most important, of the MMH (mountain, moorland and heath) habitats for delivering this service. Taken from Van der Wal et al. (2011).

Dwarf shrub heath goods and benefits	Importance
Provisioning services	
Food provision – livestock and crops: <ul style="list-style-type: none"> Livestock products from sheep and some beef cattle 	+++ *
Food provision – deer and game birds: <ul style="list-style-type: none"> Wild harvest products including venison and grouse meat 	+++ *
Fibre from sheep wool	+++ *
Traditional lifestyle products including honey and whisky	+++ *
Peat extraction for fuel and horticultural use	+
Freshwater provision for domestic and industrial use	0
Alternative energy provision: <ul style="list-style-type: none"> Opportunity for wind energy schemes Generation of water flows for hydro-energy in freshwater habitats 	+++ * 0
Regulating services	
Climate regulation: <ul style="list-style-type: none"> Carbon storage; maintenance of plant and soil carbon stores Carbon sequestration potential 	++ +++ *
Natural hazard regulation: <ul style="list-style-type: none"> Potential for flood risk mitigation Opportunities for wildfire risk mitigation 	0 +++ *
Pollution mitigation: <ul style="list-style-type: none"> Interception and retention of airborne pollutants by plants and soil Regulation of particulate matter and pH buffering Dilution by water from uplands of pollutants in downstream locations 	++ 0 0
Disease regulation: <ul style="list-style-type: none"> Disease transmission through ticks Disease regulation of waterborne bacteria (e.g. Cryptosporidia) 	++ * 0
Cultural services	
Religion and spirituality: <ul style="list-style-type: none"> Sense of awe; connection to spiritual powers Opportunities for solitude and reflection 	++ ++
Cultural heritage and aesthetics: <ul style="list-style-type: none"> Preservation of natural/environmental history and cultural practices Socially-valued ('natural' and 'cultural') landscapes Source of inspiration to works of art 	++ ++ 0
Social cohesion and community development: <ul style="list-style-type: none"> Development and maintenance of social networks through management of 'common pool' resources Landscape as symbols of a popular national identity 	++ * +++ *
Tourism and recreation: <ul style="list-style-type: none"> Outdoor active tourism and recreational opportunities Tourism and recreation based on watching wildlife Field sports (e.g. grouse shooting and deer stalking) 	+++ * ++ * +++ *
Education: <ul style="list-style-type: none"> Opportunities to learn about the natural world and cultural heritage Opportunities to learn about oneself when undertaking challenging recreation in MMH landscapes 	+++ * +
Security and personal freedom: <ul style="list-style-type: none"> Land used for Military purposes Existence value (i.e. knowing that MMH and their attributes are there) 	0 0
Human health: <ul style="list-style-type: none"> Mental and physical benefits from experiencing MMH 	0

8 Major knowledge gaps and future research options

Here we provide a simple compilation of the major knowledge gaps identified by each of the sections of the detailed review, as well some suggestions for future research options.

Hare management

- Knowledge of the current conservation status of mountain hares is reliant on incidental data and not purpose-designed surveys.
- There is a lack of knowledge of the impacts of different levels of hare population control at different population densities and phases of population change; the spatial ecology of mountain hares is also not well understood.
- The impacts of hare control on other elements of biodiversity are not well understood – this includes food-web mediated impacts on predators (and other prey, such as grouse), and impacts on some components of vegetation browsed by hares (e.g. grazing-sensitive vegetation).
- The interactive effects of hare control, hare population dynamics and other grouse moor management activities are not well understood, and what understanding there is is mostly based on correlational data.

Legal predator control

- The link between predator control and predator population change at the wider geographic scale is unknown.
- Predators carry out a range of important ecological functions; the full impacts of reduced abundance of predator species, some of which are also important scavengers, are unknown.
- There is a distinct lack of knowledge about how removal of one, or a range of, predators affects other predators and the wider food web. Overall the effects of predator control on wider biodiversity are poorly understood.
- The extent and intensity of different types of legal predator control are not documented in the scientific literature.
- There are concerns over the unintentional trapping and killing of non-target species (bycatch), but we know very little about this in Scotland.

Muirburn

- Fire intensity seems to be critical in determining severity of impact, but most studies have not recorded this. This undoubtedly also interacts with fire frequency and might in part explain some of the apparently contradictory findings about biodiversity impacts of different fire frequencies - we found no studies examining such interactions and testing to what extent they might drive differences in muirburn impacts.
- There appears to be variability between different moorland habitats in susceptibility to muirburn, but much of the evidence is inconclusive; the response of species and vegetation types is highly variable and context-dependent.
- Other than studies of the impacts of muirburn on seedbanks, we found no direct studies of the impacts of muirburn on below-ground biodiversity. Depth of fire penetration seems to be a key factor, but data are lacking or inconclusive.
- It is not known what proportion of moorland in Scotland has never been burnt, or what proportion would remain heather-dominated long-term in the absence of fire.
- There is little comparative information on the impacts of heather burning vs. cutting; there are a few studies of the impacts on heather, and conclusions concerning the relative impacts on other elements of biodiversity are mainly speculative.

- There is a need to understand how fire risk and impact might change under future climate change – this also links to the next point.
- We found very limited published data on the proportions of wildfires caused by out of control muirburns and only Luxmoore (2015, 2016) showing a graph of temporal changes in such proportions (2009-2014 using SFRS data with their associated uncertainties of causal attribution). It would be informative to gather and analyse longer-duration, including more recent, time series data on this (e.g. analysing any annual differences in wildfire causes against climate data) - Scottish fire and Rescue Services supply their data on request, and we expect that many estates also keep their own data.

Grazing

- There is a lack knowledge of the long-term interactive impacts of grazing and burning.
- There is limited information on the short-term impacts of grazing on heather regeneration and how grazing can help or hinder grouse moor management.
- There is limited information on how grouse moor managers decide on whether grouse (or livestock or deer) are the main focus of their management.

Ecosystem services

- It is hard to attribute the delivery of some ecosystem services to specific habitats in wider upland areas, and few studies – even those focussing on heather moorland – explicitly examine the delivery of services by areas specifically managed for driven grouse shooting.
- Information on the delivery of some services types – especially cultural ecosystem services – is particularly lacking, as is our understanding of the role of particular components of biodiversity.
- Although it may be critical, we have a poor understanding of the role of people in delivering services and benefits in moorland systems, and for some services how ecosystem service potential is converted into delivered services through such interactions.
- The impacts of moorland management on service delivery are complex, often indirect, and often context -dependent, and our knowledge of these relationships is limited.

Future Research Options

To address the identified knowledge gaps, here we propose some future research options. We have prioritised these (high, medium, low) based on a combination of difficulty of delivery and the immediate importance of the evidence gap.

- Link new data emerging from analyses undertaken in this study – for example GIS-based estimates of grouse moor management intensity – with other geographically explicit datasets of biodiversity impacts (e.g. changes in populations of key species; distributions of confirmed raptor persecution incidents). It is important to include temporal analyses as well as spatial, to address questions relating to frequency as well as spatial-intensity of muirburn and other moorland management activities. – *High priority.*
- Develop the new GIS-based techniques to assess the area of land in Scotland under management for driven grouse. – *High priority.*
- Further investigate the role of muirburn in causing wildfires and/or protecting against large wildfires through reducing fuel loads. This can be done by collecting and interrogating SFRS and other documented information on wildfire causes. Annual data collection by SFRS (and possibly many estates?) gives the opportunity to examine both temporal and spatial patterns, linking these to climate and land management data. – *High priority.*
- Assess the distribution, intensity and impact of hare management and legal predator control, including assessment of by-catch by legal predator control. – *Medium priority.*
- Detailed assessment of hare-louping ill-grouse relationship. – *Low priority.*

Future research could also focus on purpose-designed experimental studies that:

- Compare areas of moorland managed and not managed for driven grouse shooting, enabling an explicit assessment of driven grouse shooting impacts.
- Manipulate the intensity of specific management activities (e.g. predator control, hare population control, muirburn) in a controlled fashion (and also possibly in combination with other factors, such as grazing, to look at interactions).
- Are adequately replicated to account for the impact of context (social and environmental) on responses.
- Are adequately monitored (for example recording muirburn fire intensity, or the response of target organisms such as hares or controlled predators outside – as well as inside – the management area).
- Analyse impacts of different intensities of muirburn on below-ground biodiversity. This would be labour-intensive work but would address an area with almost no current information.
- Examine the responses of both biodiversity and ecosystem service delivery, including tackling those services commonly overlooked (for example cultural ecosystem services).
- Explore the role of people in converting ecosystem service potential to generated benefits.

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Appendix A. – Identifying impacts for detailed review

As part of the project *The socio-economic and biodiversity impacts of driven grouse moors in Scotland* the JHI review team has committed to deliver the following:

An initial *phase* of the literature review will be structured in relation to selecting a subset of the following key management activities associated with driven grouse moors:

- Heather burning
- Grazing (sheep and deer)
- Construction of hill tracks
- Use of medication
- Predator control
- Hare control
- Draining or drain blocking
- Use of lead shot.
- Wider environmental impacts (climate change effects of muirburn and peat degradation)

This initial phase will identify a smaller subset of impacts (3-4) for focussing on in more detail based on: severity of environmental impact, availability of current evidence, whether the impact is a general issue for driven grouse moors. The impacts for more detailed review will be agreed with the Research Steering Group, and assigned to individuals within the review team which will also undertake cross-checking of draft text as it becomes available. Methods used will be standardised (for example as per previous peatland muirburn reviews for CXC⁴).

This document sets out our process for selecting, and proposal for, the smaller group of impacts to focus on in more detail in the literature review. When considering which of the “long list” should be taken forward as focal topics we have taken into account a number of factors:

1. Availability of evidence; there may be relatively little evidence available as to the impacts of some management activities. In these cases a literature review will be of very limited use, and these might be considered targets for future research. To assess the availability of evidence we have undertaken preliminary searches of the scientific literature using the online Web of Science service⁵. We have also looked for recent subject reviews published since that of Werritty *et al.* (2015).
2. Severity of the environmental impact of the management activity, both in the immediate vicinity of the location where it’s undertaken and at a larger spatial scale.
3. Whether the management activity is mainly associated with management for driven grouse or whether it might be undertaken for other reasons.
4. Needs of the Grouse Moor Management Group (GMMG), including resources (e.g. the existing evidence base) already available to them. As our work feeds into the GMMG’s activities it is sensible that we focus on management activities which are of particular interest to the Group, and where a detailed evidence review can help support the GMMG’s work.

A1. Assessment of the “long list”

Based on this set of criteria we have undertaken an assessment of the management activities in the long list. Whilst there may be management activities not covered by this list, this list was updated following the project initiation meeting and having now also looked over the wider literature we feel it covers the major management activities associated with driven grouse moors.

⁴ Chapman et al. (2017) Muirburn, Peatland and Peat Soils – An evidence assessment of impact. Climate-X-Change, Edinburgh, https://www.climateexchange.org.uk/media/2063/muirburn_peatland_and_peat_soils_-_an_evidence_assessment.pdf

⁵ <http://wok.mimas.ac.uk/>

Heather burning

There is a substantial body of evidence on the impacts of heather burning. A Web of Science search on the topic indicated >100 relevant references including reviews that could be updated with more recent publications, some of which have major new findings. Making no assumptions about whether they are positive or negative, the environmental impacts of muirburn are clearly substantial both for local vegetation and associated biodiversity, and more widely due to smoke and GHG emissions. Whilst muirburn is associated with other management activities, e.g. promoting forage for grazing, it is strongly associated with management for driven grouse. Muirburn is considered a priority issue by the GMMG.

Grazing (sheep and deer)

There is a very large body of literature on the impacts of grazing management. Clearly much of this will not be relevant to grazing management on driven grouse moors. However, we estimate our search identified >200 references of relevance to moorland grazing impacts. Grazing impacts in upland systems can be substantial and widespread, as indicated by recent studies of deer management in Scotland and of the impacts of vegetation change following grazing cessation across Europe. Grazing is not undertaken explicitly as management for driven grouse, but is commonly part of the overall management regime for land where driven grouse management takes place (e.g. combined sheep or deer grazing and driven grouse shooting). Grazing is considered a priority issue by the GMMG.

Construction of hill tracks

We found very little information on the issue of hill tracks in Web of Science – of the 26 papers identified, none have tracks as a primary focus, and very few of these appear to be genuinely relevant. This reflects the review of the issue of hill tracks by Werritty et al. (2015) who reported little evidence and much supposition/concern. Although having substantial aesthetic impacts (as indicated by the level of current public debate), other environmental impacts of hill tracks are less clear and - we suggest - limited compared to some of the other management actions in the long list. Hill tracks are constructed for a wide range of reasons, including hydro-power developments, although track construction and maintenance is in some areas an activity clearly associated with driven grouse shooting.

Use of medication (e.g. medicated grit)

Although this is an issue of interest for the GMMG, a thorough review by specialist researchers has been recently undertaken and passed on to the GMMG. In addition some animal health issues (for example the role of grazers in influencing grouse parasite burden) can be covered under other topic areas such as hare control or grazing.

Predator control

With respect to illegal control (of raptors) a comprehensive review has already been undertaken for the GMMG by the recognised expert: Ian Newton. Legal predator control (foxes, stoats, weasels, and crows), is a management activity strongly associated with driven grouse shooting used to increase grouse breeding success and survival. Predator control to benefit grouse also benefits some other ground nesting birds and possibly mammals such as mountain hares. Our initial Web of Science search combined with searching the bibliographies of recent reviews identified > 20 relevant papers describing experimental and correlation studies on the impact of predator control on non-target species. Although the evidence base is smaller than that for, for example, mountain hare control or grazing, legal predator control is a priority issue for the GMMG.

Mountain Hare control

There is a substantial evidence base available for review on the environmental impacts of hare control; our initial search identified > 100 papers. Although having a relatively restricted environmental impact, this is a management activity strongly associated with management for driven grouse

shooting, in part due to the desire to manage grouse pest (ticks) and diseases (LIV) where mountain hares are both a tick host and disease reservoir. Hare control is a priority issue for the GMMG.

Draining or drain blocking

Our Web of Science search indicated only six references directly relating to moorland and drains; other papers were identified but drains were not the primary focus of the work and may contain limited information. Although having substantial environmental impacts in terms of altering upland vegetation and hydrology, drains are not established solely for driven grouse shooting, for example the substantial drainage associated with afforestation of areas of the Flow Country. Existing reviews (e.g. Werrity et al 2015; Chapman et al 2016), reports and guidance notes (for example by from GWCT, Natural England, RSPB) give reasonable summaries of the impacts and we do not think we would find anything additional that is radically different and could add to the information already available.

Use of lead shot.

The Lead Ammunition Group's 2015 report to Defra⁶ explored the risks to wildlife from the use of lead ammunition although this did not focus on driven grouse moors. Likewise whilst lead shot as a topic does elicit a high number of references on Web of Science, very few of these are studies of grouse moors. Whilst obviously a management activity strongly associated with driven grouse shooting, we cannot comment on the extent or severity of the environmental impacts of lead shot use on grouse moors, and feel there would be relatively little information beyond that already gathered in the more general reviews by the Lead Ammunition Group that would allow us to do so.

Wider environmental impacts (climate change effects of muirburn and peat degradation)

On reflection we feel that the inclusion of this topic in the long list is not helpful; it is explicitly about impacts (i.e. outcomes) rather than the management actions that might drive them. In addition these wider environmental impacts can be picked up when reviewing the consequences of management actions. For example, GHG emissions and peat degradation can be considered during a review of the effects of muirburn. These issues can also be included in the component of our review work focussing on the ecosystem service effects of management for driven grouse.

Finally we think it is interesting to note that the outcome of our preliminary Web of Science searches is reflected in the literature list provided by Ian Thomson (RSPB, project steering group). A quick analysis of the list indicates a lot of available evidence on burning (roughly 30% of references), with tracks and drains having the lowest number of relevant references.

A2. Recommendation

Based on the above assessment we recommend that the detailed evidence review focusses on the environmental impacts of heather burning, grazing (sheep and deer), legal predator control and mountain hare control.

Overall, the benefits of focussing on these management activities are that:

1. These management activities can have substantial and often wide-reaching impacts.
2. These management activities are strongly associated with management for driven grouse.
3. Our initial searches of the literature indicate that there is a good evidence base to draw from.
4. For some of these management activities we have already gathered in-house a strong evidence base, particularly for the impacts of muirburn and hare management. This helps us to work efficiently and to tackle four rather than three management activities as part of the review, in particular helping us to address the issue of grazing which has the largest literature of all the topics on the list.

⁶ <http://www.leadammunitiongroup.org.uk/reports/>

5. These topics map onto the priority issues for the GMMG.

Management activities which might be considered for more investigation in future research, on the basis of a lack of evidence and strong association with driven grouse shooting, are hill tracks and the use of lead shot.

Appendix B. Sources of information

B1. Mountain hares

The primary sources of information used were the literature reviews, and associated literature, on the ecology and population dynamics, conservation status, management, and population cycles of mountain hares (Newey et al. 2007a, b, Newey et al. 2008, Harrison et al. 2010, Harrison 2011), along with the SNH's Review of Sustainable Moorland Management (Werritty et al. 2015). To identify more recent literature, we carried out literature searches of the Web of Science and Google Scholar using the search terms; (topic = ((moor* OR upland OR grouse) AND (mountain hare OR "L. timidus" OR "Lepus timidus")) for articles and reviews published since 2015 (date last accessed 31/08/2018). Research reports from government and non-government organisations are used where these provide policy or relevant information (e.g. JNCC quinquennial Article 17 reporting, British Trust for Ornithology's Breeding Bird Survey reports) not provided elsewhere.

The Web of Science search identified six peer-reviewed and published papers, but only two papers were relevant and were based on Scottish studies (i.e. Gilbert 2016, Fletcher & Baines 2018), and failed to identify two highly relevant papers published in August 2018 that we were already aware of (i.e. Massimino et al. 2018, Watson & Wilson 2018). The equivalent search in Google Scholar identified seven references, one of which was also identified in the Web of Science search (Fletcher & Baines 2018), relating to mountain hares including (Watson & Wilson 2018), but excluding (Massimino et al. 2018), with six pertaining to Scotland (Baines & Taylor 2016, Thompson et al. 2016, Young et al. 2016, Sotherton et al. 2017, Fletcher & Baines 2018, Watson & Wilson 2018).

B2. Legal predator control

The primary sources of information used were the recent literature reviews, and associated literature, on the effects of predator control and gamebird management on biodiversity by Mustin et al. (2018) and Roos et al. (2018), along with the SNH's Review of Sustainable Moorland Management (Werritty et al. 2015). We were aware of Gibbons et al. (2007), but this report is largely superseded by Roos et al. (2018); however, we note that Gibbons et al. (2007) provides an accessible overview of the topic and introduction to key concepts for non-specialists. To identify more recent literature, we carried out literature searches of the Web of Science and Google Scholar using the search terms topic = ((moor* OR upland OR grouse) AND ("predator control" OR "predator reduction")) for articles and reviews published since 2015 (date last accessed 07/09/2018). All articles were for assessed for relevance and excluded if they did not relate to assessing the biodiversity impacts of legal predator control in relation to moorland management for red grouse shooting. Research reports from government and non-government organisations are used where these provide policy or relevant information (e.g. British Trust for Ornithology's Breeding Bird Survey reports) not provided elsewhere. We draw on the wider ecological literature as needed to explain underlying concepts and to address specific knowledge gaps in evidence directly relating to grouse moor management.

Web of Science returned 15 publications, of which three were relevant and matched our selection criteria (Douglas et al. 2014, Buchanan et al. 2017, Mustin et al. 2018). Notably the Web of Science search did not identify a few key papers (e.g. Thompson et al. 2016, Newey et al. 2016b). The same search using Google Scholar identified six papers that broadly matched our search criteria, but on examination just one fully matched the time-span and geographic limitations (Ludwig et al. 2017). We did not expect either search to identify Roos et al. (2018) as this article is not yet been assigned to a journal volume and is only available as "early view".

B3. Muirburn

The primary sources of information used were the publications (primary data and reviews) located using the Web of Science Search plus: references sent in by our contract steering group; reports that we located from keyword searches of SNH, JNCC, EN, Heather Trust and other relevant websites; plus additional references already known to ourselves that the Web of Science search had not picked up. The Web of Science search was carried out as follows:

TOPIC=((moor* OR upland OR grouse) AND (burn* OR *fire OR muirburn OR swaling) AND (UK OR united kingdom OR England OR Scotland OR Wales OR Ireland OR Brit*))

Timespan: All years (up to August 2018).

Indexes: SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, ESCI.

This gave 309 results, 86 of which addressed fire impacts on moorlands (including both muirburn and wildfires) in the UK. We also included 2 non-UK reference that were considered to be helpful to the review: Velle et al. (2014) from Norwegian heathlands and Lukenbach et al. (2016) from Canadian peatland. This list included references dealing with *any* aspect of impact of burning impacts, not just biodiversity impacts, which is the focus of this section. Papers on wider ecosystem impacts have been included in the section reviewing impacts of grouse management on ecosystem services. We did not limit ourselves to Scotland since there is also much relevant work done elsewhere in the UK. When we had added in the additional references from the steering group, Agency and NGO websites and our own collections, the total number of references was 106. All these references were checked, are included in the Reference list, and relevant findings are reported and referenced in our review.

There have been a number of relatively recent reviews of relevance to this remit, which we have drawn upon in detail (with our own additional checks of the literature quoted). A review on muirburn impacts on soil carbon and biodiversity was carried out by Towers et al (2010). There have been two recent major evidence reviews carried out for impacts of managed burning on peatlands/peat soils (as these are thought to be the most vulnerable moorland types to detrimental impacts of muirburn): a Natural England review (Glaves et al. 2013) and a Scottish Government CXC review (Chapman et al. 2017). The Werritty et al. (2015) review of 'sustainable moorland management' for SNH also includes a short summary on muirburn. Our review brings the evidence up to date with the inclusion of more recent publications, as well as some references that were not included in the previous reviews (they did not have exactly the same remit as this review). Since the most recent of those reviews, there have been further primary data publications, some from major research projects, additional reviews, and also much debate in other literature about the existing evidence-base.

B4. Grazing

Grazing management differs from the other focal management activities considered in this review (muirburn, and hare and legal predator control) because grazing is often not occurring primarily to promote driven grouse shooting. Grouse moors are often used as a grazing resource for livestock farmers; most commonly with sheep and more rarely with cattle. Most moors are also grazed by red deer. However, the nature of grazing may be altered if an area of land is managed for driven grouse shooting, and this has direct effects on the vegetation and can interact with other management activities such as muirburn.

The majority of the information used in this section is taken from the scientific literature. The searching used Web of Science and Google Scholar using the search terms (moor* OR upland OR grouse) AND (graz* OR brows* OR browz*) AND (UK OR United Kingdom OR England OR Scotland OR Wales OR Ireland OR Brit*). The resulting list was supplemented from the review of the impact of grazing on moorland biodiversity carried out as part of Natural England's upland evidence review (Martin et al. 2013). A more general summary of moorland management (Werritty et al. 2015) was also checked to see if this had covered the literature more extensively. All articles were assessed for

relevance and excluded if they did not relate to assessing the biodiversity impacts of grazing or browsing in relation to moorland management for red grouse shooting.

The works cited on grazing and its relationship to grouse moor management are largely Scottish. The main exception to this is papers from Moorhouse in the North Pennines. However, as no equivalent long-term studies have been done in Scotland, then this site provides much of the best evidence on the long-term effects of both grazing and burning.

B5. Ecosystem services

In this section we consider the implications for wider ecosystem service delivery arising from management actions associated with driven grouse moors. In order to explore the links between biodiversity and ecosystem service provision in areas managed for driven grouse shooting in Scotland, and how management impacts on biodiversity might affect ecosystem service delivery, we have addressed the following three questions:

- What ecosystem services do areas managed for driven grouse shooting provide?
- What regulates these ecosystem services?
- What are the impacts on ecosystem services of management actions strongly associated with driven grouse shooting?

This overview is intended to be 'lighter touch' than the detailed review of the biodiversity impacts of specific management actions. However, for the sake of consistency we have taken a broadly similar approach to identifying relevant literature. Specifically we took as our starting point the UK National Ecosystem Assessment, in particular the chapter by Van der Wal et al. (2011) on Mountain Moorlands and Heaths. To identify more recent literature we carried out literature searches on the web of Science and Google Scholar using the search terms: topic= ((moor* OR upland OR grouse) AND ("ecosystem service*" OR "natural capital") AND (UK OR united kingdom OR England OR Scotland OR Wales OR Ireland OR Brit*)) for articles and reviews published since 2011. The results of this search was augmented by publications recommended by members of the project Steering Group.