Impacts of Burning Management on Peatlands

Worrall, F.[1], Clay, G.D.[1], Marrs, R.[2], and Reed, M.S.[3]

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[1] Department of Earth Sciences, Durham University, Science Laboratories, Durham, DH1 3LE
[2] Applied Vegetation Dynamics Laboratory, School of Environmental Sciences, Nicholson Building, Crown Street, University of Liverpool, Liverpool L69 3GP
[3] Aberdeen Centre for Environmental Sustainability, Centre for Planning & Environmental Management and Centre for Sustainable International Development, School of Geosciences, University of Aberdeen, St Mary's, Aberdeen AB24 3UF

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Summary

- In the UK, peatlands support a variety of important habitats and rare or threatened species. Peatlands also provide many key ecosystem services such as water provision, flood management and carbon storage. However, all these ecosystem services are affected to varying degrees by land management and human intervention.

- One regularly practiced management technique on peatland is prescribed, or managed, burning. The aim of burning is to remove the older, less productive vegetation and to encourage new growth for livestock grazing and for red grouse (*Lagopus lagopus scotica)* production. Burning also can on one hand reduce the fuel load on peatlands, particularly those dominated by heather (*Calluna vulgaris*) , which may alter the impact of any successive wildfires but on the other land leads to a perpetuation of the heather-dominated vegetation and cycle of having to reburn it (e.g. Lindsay, 2010). Burning occurs across many regions of the UK and recent estimates suggest that 18% of UK peats are subjected to prescribed burning; however, it is unevenly distributed with less burning in parts of Scotland and lowland peatlands.

- This review assessed the current status of prescribed burning within the UK and collated current and ongoing research results that investigate the effect of burning on ecosystem services. By using a formalised review process that assessed both the magnitude and direction of any burning effect, the review was able to draw together findings from across the published peer-review articles and ‘grey’ literature e.g. government reports, unpublished articles.

- The review noted that prescribed burning can bring positive and negative effects for a range of ecosystem services. For example, burning has been observed to increase grouse and sheep production; however, burning has also been noted to negatively affect the presence of some flora and fauna species e.g. meadow pipit (*Anthus pratensis)* and some *Sphagnum* species.

- For some ecosystem services the evidence is equivocal, e.g. positive and negative effects have been noted for the impact of prescribed burning on water quality and concentration of dissolved organic carbon (DOC) in particular.

- This multitude of effects across different peatland habitat types leads to difficulties in creating generalised conclusions for the impact of prescribed burning.

The review can make the following recommendations and has identified the following challenges

- Prescribed burning may bring both benefits and dis-benefits for some ecosystem services

- Individual stakeholders will have decide which ecosystem service or suit of ecosystem services is the priority in any particular locality.

- Further research is required into many aspects of prescribed burning and this review has highlighted suggested areas for investigation.

- Many of the results from the literature are based on studies that compare the presence with the absence of burning. Few studies compare styles of burning e.g. size of burn strips, methods of ignition and whether more or less intense. The review would suggest that this is a key area of research for the benefit of policymakers and practitioners alike.

1. Introduction

The purpose of the IUCN programme is to provide a set of briefings on the consensus on the state of peatlands in the UK and the impact of different activities on the ecosystem. The programme aims to investigate blanket bog quality and develop best practice for restoration and monitoring. This review aims to investigate the impact of burning management on peatlands and to reflect on the variety of ecosystem services that burning affects. Prescribed burning is used worldwide for vegetation management; however, there is concern about its environmental impacts.

The regular burning of peatland habitats[1], for the purposes of vegetation re-growth for livestock or red grouse, has shaped the upland landscapes of the UK for many centuries. Burning alters vegetation composition and structure and whilst it may in some circumstances enhance biodiversity through the enhancement of fire-adapted species, it may be damaging to biodiversity by reducing fire-sensitive species. Inappropriate burning is cited as a reason for poor ('unfavourable') condition of designated sites in England (Natural England, 2008). The latest data on the condition of Blanket Bog within SSSIs in England found that only 11% by area are in favourable condition, although 83% is in recovering condition mainly on the basis of management agreements and other measures in place (Natural England, pers. comm.). Primary reasons cited for unfavourable (no change or declining) condition are overgrazing, inappropriate 'moor burning' and drainage.

Peatlands support many habitats such as dry heath, wet heath, raised and blanket bog, other mires, fens and swamps. However, there are many classifications and terminologies that are often used interchangeably sometimes leading to confusion in the literature. For example in the UK uplands, there are 28 upland feature types that cover 91 National Vegetation Classification (NVC) community types included in the Common Standards Monitoring Guidance (JNCC, 2009), though only a few are characteristic of peatlands.. Combined with this the condition of the peatland is also another factor that can be added to descriptions. For example, active peat forming bogs are usually described as diplotelmic, i.e. having a two-layered structure comprising an acrotelm and a catotelm. Where bogs have been damaged, this can breakdown to form a single-layered (haplotelmic) bog. It has been suggested that in the latter case the long-term carbon store may be steadily being lost (Lindsay, 2010).

Here favourable and unfavourable have technical definitions in the assessment of the condition of designated sites based on mandatory attributes for which each habitat must meet a minimum threshold to be regarded as in favourable condition (JNCC, 2009). Thus, the vegetation composition and condition of study sites is a key issue in the interpretation of the evidence included in this review which may influence the extent to which results can be extrapolated more widely. It may also mean that different management may be appropriate to peatlands in different condition. This applies particularly to the difference between severely-modified,

[1] Working definitions of peatland habitats are outlined in section 1.2

degraded peatlands (usually dominated by a few species, particularly *Calluna vulgaris*[2] and *Molinia caerulea*) and 'active' peatlands characterised by more varied wetland, mire vegetation usually including *Sphagnum* mosses (Bog-mosses).

There have been a series of comprehensive reviews of the impacts of burning, particularly on biodiversity and in the uplands (not just peatlands) and more recently on wider environmental interests services (Glaves and Haycock, 2005; Shaw et al., 1996; Tucker, 2003) and wider reviews of moorland and peatland management and issues including (e.g. Coulson et al., 1992; Lindsay, 2010). These reviews all suggested that burning is, or could be, damaging to peatlands and in some cases recommended that it should not be carried out. As a result there is a presumption against burning on blanket bog in England (Defra, 2007a), Wales (Welsh Assembly Government, 2008) and Scotland (SEERAD, 2008). Nevertheless, the practice does occur on these active peat forming areas and is agreed to in some burning management plans.

Therefore, this review aims to provide a summary of current data from research into prescribed burning on peatlands and to provide informed opinion on this current thinking. There are already several comprehensive reviews mentioned above that address the effects of prescribed burning on a variety of ecosystem services so it is not the place of this review to redo the efforts of those authors, but rather to draw together studies that have been published since these major reviews.

By reviewing the questions posed at the end of many of these reviews on the data gaps and the research questions still to be posed, this review will seek update these questions in line with recent research.

1.1 Aims and scope

This review will concentrate on in the impact of burning on four main topics:

- Biodiversity
- Hydrology
- Carbon and greenhouse gas balance
- Socio-economic impacts

Throughout the review and in each of these four topic areas the underlying aim is to investigate the question of "what do we know/not know?". By better understanding knowledge gaps we can start to address what actions need to be taken now in order to prepare for future changes.

1.2 Working definitions

In addition to some definitions already detailed above, the following assumptions and definitions of prescribed burning and of peatlands, are made:

a) Peats are defined as deep peats with an organic layer deeper than 40 cm depth which coincides with the definition used within the Soil Survey of England and Wales, or 50 cm deep in Scotland.
b) The review includes peat soils in blanket bog and mires in both upland and lowland settings. The review does not consider wetlands with large expanses of standing water nor peat soils converted for arable agriculture. The glossary in JNCC report 445 (JNCC

[2] Nomenclature follows Stace (1997) for higher plants and Atherton et al. (2010) for bryophytes. Authorities for other species are provided at first mention

2011) defines the terms used in this report including habitat types such as blanket bog, fen, and mire

c) In geographical terms the review considers data from the UK as a priority but also considered data from Europe and North America, but data from the Arctic or which could be considered as tundra were excluded.
d) The context in which peat soils are considered is not stationary especially in the light of climate change, but given the scarcity of studies it was decided not to discriminate on the grounds of age of the study.
e) Prescribed burning is considered as any deliberate and prescribed burning of vegetation on peat soils. It does not include the burning of peat soil as fuel and deliberate acts of arson. Although this definition does not include accidental fire we will consider the impact of prescribed fires that become runaway burns. We consider burning across a range of vegetation and for a range of reasons including: increasing grouse and sheep production; and for wildfire risk reduction.
f) Terms such as fire intensity and fire severity are often incorrectly used interchangeably. The definitions of Keeley (2009) are useful when considering impacts of fire and further information on these important definitions is given in section 2.1
g) The exact definitions of prescribed burning and of peat soils may vary between studies and the review has had to accept the author's individual statements.
h) We have to be generous with the authors' definitions regarding peatland type, classification or habitat that may include data from non-peat soils. We recognise that many useful peatland classification exist, however, given the nature of our data and the size of our dataset, imposing any particular set of subdivisions may prove fruitless as they are not represented in the data.
i) The review has to rely on the individual authors and a critical assessment of data quality of any individual study is not possible within this review, however, studies are classified depending upon their status, e.g. studies in peer-reviewed journals will be considered of superior quality to project reports.
j) The review attempts to consider both magnitude and direction of any effect.

2. History, aims of burning and current practice

Fire has been a common part of the uplands of the UK for many hundreds, even thousands, of years. Whilst there is evidence that fire may have been used to clear land since Neolithic times (Fyfe et al., 2003), it was not until the late medieval period when burning started to become a common management practice. Records show that burning, or 'swaling' was a common practice on Exmoor in the 1300s to improve pasture (Rackham, 1986) and records in Scotland show the term 'muirburn' occurs in an Act of Scottish Parliament of 1400 (Dodgshon and Olsson, 2006).

The use of prescribed burning for habitat management for red grouse (*Lagopus lagopus scoticus)* spread rapidly during the middle of the 19th century. Prior to this, burning was carried out to improve grazing for sheep (*Ovis aries*) and red deer (*Cervus elaphus*) and this practice also continues today. Burns for sheep and deer management are often larger than those for grouse and have the aim of creating large areas of more palatable regenerated vegetation. The current method of strip burning was known to occur in the 19th century, however, it was not until an inquiry into grouse disease in 1911 (Lovat, 1911) that the practice started to become codified.

Management for red grouse aims to create a mosaic of new growth for forage whilst maintaining older stands of heather for cover. Through repeated cycles of burning heather (*Calluna vulgaris,* hereafter known as *Calluna*) is prevented from reaching a degenerate phase (Hobbs and Gimingham, 1987).

In the 1970s and 1980s a series of studies investigated the effects of burning on heathland vegetation (e.g. Hobbs, 1984; Hobbs and Gimingham, 1984a; Hobbs and Gimingham, 1984b). Studies have also investigated the impact of burning on other biophysical processes, but in recent years, concern over the nature of peatland carbon stores have prompted a series of works looking at the impact of burning on carbon stores and fluxes (e.g. Garnett et al., 2000; Ward et al., 2007)

3. Status and trends

3.1 Types of burning

There are at least four different types of fire (Glaves and Haycock, 2005) although definitions vary across the world, these are:

(a) Prescribed burning, sometimes called managed or controlled burns, where the fire has been deliberately lit for management purposes. In the UK prescribed burning is controlled by legislation.
(b) Wildfire – according to the definitions of (CIFFC, 2002; NWCG, 2008) are any unwanted or unplanned fires; this can be sub-divided into at least three types:
    a. Escaped prescribed fire, where the fire has moved beyond the planned fire boundary and is out of control.
    b. Human-induced fires started accidentally or negligence (barbecues, smoking, discarded glass) or started deliberately (arson)
    c. Natural-fires started by lightning.

The review of terminology by Keeley (2009) provides a good systematic framework to consider the impacts of these different types of fires and argues that there should be a separation in thinking over these different terms and specifically for fire intensity, fire/burn severity and ecosystem response, for example:

(a) Fire intensity should be confined to a measurement of the energy output from the fire.
(b) Fire/burn severity is the organic matter lost during combustion
(c) Ecosystem response is essentially a measure of the resilience of the ecosystem to recover to the pre-burn conditions.

3.2 Geographical extent

Prescribed burning is spatially extensive and recent surveys, using aerial imaging, have estimated that up to 114 km^2 of the English uplands (though a substantial proportion of this is not peatland) are burnt annually (Yallop et al., 2006b). Natural England (2010a) report that 15% of English peatlands have been subjected to prescribed burning which equates to 1000 km^2 out of 6780 km^2 of deep peat. Defra (2010) estimate that 18% of UK peats have been subject to prescribed burning which is approximately 3150 km^2. However, the proportion of burning varies significantly across the UK – 1-2% in Borders and Grampian (Hester and Sydes, 1992) to 20%

in the North Pennines AONB (Yallop et al., 2006a). Yallop et al. (2005), using historical and current aerial photography, show that in *Calluna*-dominated communities 38% of the area was managed by burning. In areas not normally managed for grouse, these proportions range from 1-16% (Glaves and Haycock, 2005).

Much of the literature recording burning trends in the UK is dominated by upland peats (e.g. blanket bog, dry and wet heath settings) with little recorded for lowland settings.

The typical length of rotations is an alternative way to estimate the area under burning management as it is the reciprocal of the area burnt i.e. 1/20th of the land burnt = 20-year rotation. Where it is burnt, the Code recommends rotation length on blanket peat of between 15-25 years in England (Defra, 2007a), however, again regional differences lead to a variety of common rotation lengths (Shaw et al., 1996). Some of this variation may reflect differences in the local growth rate of the vegetation and both the Muirburn Code and Burning Code highlight the need for burning rotations appropriate to the local conditions (Defra, 2007a; SEERAD, 2008). Additionally weather conditions and labour availability also affect the amount of burning that can occur during the legal burning season. Where agreed, longer rotations on blanket bog, other mires and wet heath represent a compromise as an initial step in the restoration and in some cases maintenance of these habitats. However, the Codes state that there should be a presumption against burning on blanket bog (though the Muirburn Code allows for burning on blanket bog where heather cover exceeds 75%) unless agreed to by the appropriate statutory authority e.g. Natural England, Scottish Natural Heritage (Defra, 2007a; SEERAD, 2008; Welsh Assembly Government, 2008).

From a survey of aerial photography in England, Yallop et al., (2005) show that burning appears to have increased between the 1940s and 1970s but with little change from the 1970s to 2000, though when photography from the National Parks is included a significant increase in burning is recorded from the 1970s to 2000. This demonstrates the localised regional variations in burning (Yallop et al., 2006b). Indeed in a study of burning on the High Peak estate, Derbyshire/South Yorkshire, increases in burning, both in the number of burns and total area burnt, during the 1990s were observed (Penny Anderson Associates, 2006) confirming earlier studies (ADAS, 1997). The authors suggest that these increases are due in part to the ESA agreements that grant aided an agreed burning programme. However, it should be noted that increases and decreases are also influenced differences in burning conditions and the authors note that decreases observed during 1999-2005 may be influenced by some particularly wet years leading to poor burning conditions. Davies (2008) points out that recent changes in burning regimes should be viewed as part of a long-term series of changes over the last 150-200 years.

3.3 Timing of burning

Prescribed burning is restricted to certain times of the year in order to protect ground nesting birds and other wildlife in the nesting season. It is also restricted to limit the chances of runaway fires in the hotter summer conditions, though with limited research on summer burning, where the complex interaction between fuel moisture contents, relative humidity and precipitation can drastically alter the rate of spread and fire intensity, this hypothesis needs further testing. Table 1 summarises the periods in which burning is allowed along with the principal legislation that covers this in each administration area. It is also worth noting that burning can be carried out outside of the main season under licence

Table 1 *Legislation covering prescribed burning with legal burning season*

	Uplands	Lowlands	Principal legislation	Code
England	1st October – 15th April (SDA)	1st November – 31st March	The Heather and Grass etc. Burning (England) Regulations 2007	The Heather and Grass Burning Code (Defra, 2007a)
Wales	1st October – 31st March (SDA)	1st November – 15th March	The Heather and Grass etc. Burning (Wales) Regulations 2008	The Heather and Grass Burning Code for Wales (Welsh Assembly Government, 2008)
Scotland[3]	1st October – 30th April (above 450m)	1st October – 15th April (below 450m)	Hill Farming Act 1946	Muirburn Code (SEERAD, 2008) Muirburn code supplement (SEERAD, 2001)
Northern Ireland	1st September – 14th April		Game Preservation Act (N.I.) 1928, Chapter 25 as amended by the Game Law Amendment Act 1951, Chapter 4	

As Table 1 shows, the restriction period for burning varies across the country and for uplands vs. lowlands. One of the outcomes of the Glaves and Haycock review (2005) was to say that “the Panel **do not recommend** any changes to the **existing burning dates** at present” [emphasis from Glaves and Haycock (2005)]. However, it goes onto say “though, given that the impacts of controlled burning earlier in autumn are uncertain, the Panel supports the suggestion of further research on this”.

Recent reviews by the British Trust for Ornithology (BTO) that investigated the breeding periods of selected bird species generally in England and on moorland in the UK, showed that some of the earliest egg laying attempts for species such as golden plover (*Pluvialis apricaria* (L.)), lapwing *(Vanellus vanellus*), Short-eared Owl (*Asio flammeus)* and Stonechat (*Saxicola torquata*) are made during early April i.e. within the current burning window in England (Joys and Crick, 2004). Moss et al. (2005) concluded that “bringing the 15th April cut-off date back to 31st March would remove the earliest breeding species from significant risk”.
It should be noted that the fledgling dates for many of these species are after the current burning window (Joys and Crick, 2004). In light of these breeding dates and concern over early-

[3] In Scotland extensions can be granted for burning to 15th May (above 450m) and 30th April (below 450m)

emerging reptiles, it has been suggested that to reduce the risk of damage to nests that the end of the burning season could be moved forward, for example to the end of March as it has in Wales

3.4 Methods of burning

The methods of preparing, igniting and controlling prescribed burns have been refined over many generations and today utilise the knowledge of the past with the technology of today. In reference to grouse moor management traditionally burns would be started by paraffin kettles with a lit wick, a drip-torch (Davies et al., 2009) and, if no suitable natural fire break were available, an area would be burnt to create a fire break. Teams of keepers would use firebeaters to keep the fire in the designated area and to control its passing. Today many of these methods are still used but have been supplemented by pressurised flame-guns to start the fire coupled with various approaches to fire control including the use of fire fogging equipment, the creation of fire-breaks using mowers on quad bikes with low impact tyres and the spreading of fire-retardant foam. These innovations can allow burning to take place in conditions that otherwise would not be ideal for traditional burning and allow much better fire control management. Burning management for livestock or deer follows many of the same principles as outlined above except that the fire size tends to be larger in order to provide sufficient new growth for forage. Much of the research presented in this review comes from areas burnt as grouse-moors but it should be remembered that burning for livestock and deer is also widespread.

Burning techniques may also have an influence on fire severity. Traditional techniques, such as the use of ‘fire kettles’ (paraffin containers with a wick) to light vegetation only work well with relatively dry vegetation (and hence often can only be started late in the day). By contrast, the more recent use of gas or diesel pressurised burners allows burning of damper vegetation and burning to be carried out in a longer weather window and provide the burning of vegetation with a higher moisture content (G. Eyre, pers. comm.). The latter technique has been described colloquially as “cool burning”, but it might be better described as “fuel-assisted burning”.

Whilst new techniques may help ignite a fire in less than ideal conditions, the vegetation must still sustain the fire. Research around sustainability of a fire through vegetation such as *Calluna* is limited though work by the FireBeaters project [4] has investigated factors controlling the rate of spread fires in *Calluna* dominated habitats (Davies et al., 2009) and found that wind speed largely determined rate of spread but that vegetation structure was also an important factor. In a follow up study investigating factors controlling post-fire regeneration, Davies et al. (2010) show that post-fire regeneration was strongly linked to stand age and post-fire substrate type but that fire behaviour and severity had little effect. These results show that there are significant non-linearities in fire severity

However, it must be noted that all prescribed management fires require a detailed local knowledge of the area and understanding of fire. By passing on the inherited knowledge of prescribed burning through the generations, for example from head keeper to under keeper in the case of grouse-moor estates, these important skills can be preserved. Additionally, courses on prescribed burning held by organisations such as the Heather Trust, and links with the Fire and Rescue Service through regional fire groups[5] all allow good practice to be shared.

[4] http://www.firebeaters.org.uk/
[5] http://www.moorsforthefuture.org.uk/mftf/information/FOG.htm

Meteorological conditions can affect the fire conditions significantly and the Muirburn Code (SEERAD, 2008) and the Heather and Grass Burning Code (Defra, 2007a) both specify wind speeds above which burning should and should not occur. As fire movement through the vegetation will be restricted at very low wind speeds, a low wind speed will self-regulate burning. Other conditions related to the weather on the day of burning such as air temperature and moisture content have been shown to affect the amount of biomass consumed during burning

4. Effects on ecosystem services and biodiversity – rationale and methodology

UK peatlands have multiple land uses and provide many outputs enjoyed by multiple stakeholders (Bonn et al., 2009a; Holden et al., 2007). These outputs often referred to as 'ecosystem services' are services that the environment provides for the well-being of humans such as clean air, water and food. Ecosystem services can be grouped into four categories following the Millennium Ecosystem Assessment definitions (Millennium Ecosystem Assessment, 2005): provisioning services (ecosystem products e.g. food and fibre); regulating services (including process such as climate regulation, flood regulation); cultural services (non-material benefits from ecosystems e.g. spiritual fulfillment, recreation) and supporting services (necessary for the production of other ecosystem services, e.g., soil formation, photosynthesis and nutrient cycling).

The impact of burning on the following ecosystem services are considered in this report:

- Regulating services:
    - Carbon storage and sequestration for climate change
    - Wildfire regulation
    - Water quality
    - Erosion control
- Provisioning services:
    - Food and wool from game and sheep
- Cultural services:
    - Landscape value
    - Cultural heritage
    - Field sports
    - Biodiversity

Biodiversity has been included here as part of cultural services but it can also be considered to be part of supporting services and also has an intrinsic value outside of the ecosystem services framework.

Current literature both published peer-reviewed articles and the 'grey' literature e.g. reports, was reviewed and results are drawn up in Tables 4-8 throughout this report. Table 2 details the key for the tables

Table 2a

Symbol	Definition
↑	Increase in the magnitude of the component
↓	Decrease in the magnitude of the component
↔	Increases and decreases found
×	No significant effect for that component

Table 2b

Cell shading	Classification
(white)	Original study from within UK
(grey)	Original study from outside the UK
(green)	Review article

To allow for comparison between studies, in each table a column indicates the habitat in which the study was conducted was included, however, it has not always been possible to make these consistent between studies

5. Effects on ecosystem services and biodiversity – review results

5.1 Biodiversity

Biodiversity in its simplest definition is the variety of life in a given ecosystem overall and is often used as a measure of health of a system. UK peatlands support several BAP (Biodiversity Action Plan) priority habitats such as upland heathland, blanket bog, upland flushes, fens and swamps and in lowland areas, lowland rasied bog and lowland fens and heathlands. They are also the habitat for some BAP species such as grey mountain carpet moth *Entephria Caesiata* and *Sphagum balticum* (Natural England, 2010b), though many of these species are also associated with a range of priority and non-priority habitats. For example, although blanket bog does not support a large diversity of species it is important for a number of specialist species (Natural England, 2010b). Internationally UK peatlands are also important e.g. ~15% of the global blanket bog resource is found in the UK (Evans et al., 2006). The IUCN Technical Review "Peatland Biodiversity" details further the various national and international designations of UK peatlands

Peatland habitats are complex mosaics of inter-linked vegetation supporting a variety of flora and fauna. Prescribed burning alters the natural state of peatlands by contributing to this mosaic and by preventing scrub invasion, though it has been shown to reduce biodiversity of some species and alter more 'natural' peatland communities leading to dominance of certain species in particular *Calluna* and, in the west, purple moor-grass (Molinia caerulea (L.) Moench.) and deer-grass (Trichophorum cespitosum (L.) Hartm.) (e.g. Averis et al., 2005; Lindsay, 2010)

They also provide a habitat for bird species such as curlew *Numenius arquata* (L.), golden plover *Pluvialis apricaria* (L.), hen harrier (*Circus cyaneus* L.), merlin (*Falco columbarius*

Linnaeus), ring ouzel *Turdus torquatus* (L.) and short-eared owl *Asio flammeus* (Pontoppidan) (Robson, 1998; Thompson et al., 1997; Whittingham et al., 2000; Whittingham et al., 2001).

Much of the research detailing the impacts on flora and fauna was comprehensively reviewed by Tucker (2003). A comment from this review was that much of the regeneration observed following fires depends on the pre-fire vegetation condition (e.g. initial floristic composition), the rotation length of burning and the fire conditions on the day of burning. Other factors such as pollution and grazing pressure will almost certainly interact with the post-fire succession. Therefore, any general conclusions on the impact of burning on biodiversity have to be treated with caution.

The impact of burning on biodiversity can be split into the effect on the flora of peatlands (Table 4) and the impact on the fauna (Table 5).

5.1.1 Flora

There are contrasting points of view with respect to the impact of fire on plant biodiversity and this to some extent depends on: (a) what is considered to be the historic vegetation; (b) the current vegetation, and indeed the vegetation that is to be conserved under existing conservation legislation; and (c) the potential target for the future.

The historic vegetation: There are many works that investigate the palaeo-ecological record of UK peatlands in the context of long-term vegetation changes (e.g. Chambers et al., 2007; Ellis, 2008; McClymont et al., 2008) and some are noted in IUCN Technical Review “Importance of Peatlands for the Historic Environment” but are not expanded upon in detail in this review.

There are published works, based on observational accounts, that some species are intolerant of fire and are damaged or even extirpated from a site after burning (Table 3 and 4). However, many of these reports, implicating prescribed burning in the decline of species, are based on anecdotal evidence and observational correlations rather than experimental evidence and many of these references also acknowledge that other factors such as overgrazing, pollution and particularly drainage may be involved. Moreover, there is often a lack of detail on whether observations are in response to prescribed burning or wildfire.

Additionally, many of these species may not occur on deep peat rather on heathland habitats with shallower peat and peaty soils. They have been included here to show fire may be linked to species decline though the extrapolation to deeper peats may be limited.

It can be argued that the totality of management on sites where these species were present has led to their decline. However, many of these species are relatively rare and do not now occur on many current peatlands where prescribed burning is implemented. There are also accounts that short-rotation burning favours some other species, for example *Rubus chamaemorus* (Rawes & Hobbs, 1979), where in this study on a blanket bog in the North Pennines, a short-rotation was 10 years.

The current vegetation: Some have argued that the current burning regime reinforces a *Calluna*-dominated vegetation that is relatively low in species (Lindsay, 2010; McVean and Ratcliffe, 1962; Rodwell, 1991). On this sort of modified vegetation, the current burning management is applied mainly for grouse and sheep, but at the same time it maintains a vegetation of low biomass relative to more mature phases of growth, and hence fire hazard. Where burning is not implemented the available fuel may increase and will likely have a high burn severity when wildfire strikes. Where this occurs the ecosystem response will also be severe as has been shown in the dry Calluna dominated heaths of the North York Moors after the 1976 fires (Maltby et al., 1990). However, this may not apply in blanket bog where the layering and growth of bog mosses may limit the available above-ground fuel. Additionally, not all wildfires are necessarily more damaging that prescribed burns and low severity wildfires can re-establish very quickly with little apparent damage to the ecosystem (Clay et al., 2010a)

The potential for the future: Future ecosystem recovery will depend on the current and previous vegetation type and condition along with a range of other factors such as grazing regime and local pollution. Studies in the Peak District (Harris & Marrs, unpublished data) have shown that on *Calluna*-dominated blanket bog managed by prescribed burning there is a flush of species (plants, mosses and lichens) in the immediate post-burn phase. Thereafter a long-term reduction in species diversity (including species richness, Shannon-Wiener Index and Simpson's Index of diversity and evenness) after burning, and that if left unburned for 50 years there is no evidence of colonization by new species. Moreover, there are very few propagules of plants or bryophytes in the surface soil and litter. Thus, on these admittedly degraded peatlands there is little hope of restoring more diverse communities without substantive intervention. However, this may not be typical of the rest of the UK situation. Such interventions might include wetting the peat by gully and grip blocking and the addition of new species. However, all of this would have to be carried out against a potential threat of summer wildfire.

Other areas many not be as degraded as these Peak District sites, and where there is a more diverse flora of peat-forming species then maintenance of these mire communities or their restoration may be easier.

Sphagnum species are key peat-forming species; however, there is little research into the effects of fire on their survival and recovery. *Sphagnum* may survive low intensity burns (Hamilton, 2000), however, in severe wildfires such as those on the North York Moors in 1976, *Sphagnum* species may be removed entirely (Maltby et al., 1990). In their study of burning and grazing at Moor House, Rawes and Hobbs (1979) showed that *Sphagnum* did recover following burning following a period of *Eriophorum vaginatum* dominance. Burch (2008) shows for wet heath sites of the North York Moors, the abundance of *Sphagnum* species was greatest at canopy heights of 30cm, though these canopy heights reflect a variety of ages and stages of *Calluna* development.

It is currently untested whether repeated cycles of burning leads to replacement of *Sphagnum* species, though hummock formers may survive fire better due to their higher moisture retention (Peatscapes Project, 2008). *S. tenellum* (Lindsay and Ross, 1994) and *S. compactum* (Okland, 1990; Slack, 1990) have been shown to be colonisers of burnt areas.

Table 3 *Species that have been reported to have declined in upland habitats of the UK, and where burning has been implicated in the decline, often in conjunction with other environmental factors such as over grazing and drainage.*

Reference	Shrub/forb	Graminoid	Fern & allies	Bryophytes
McVean & & Ratcliffe (1962)	*Pyrola media* *Solidago virgaurea*	*Luzula pilosa* *L. sylvatica*	*Hymenophyllum* spp.	Many spp.
Ratcliffe (2002)	*Hypericum elodes* *Platanthera bifolia* *Scutellaria minor*	*Carex limosa Carex magellanica*		*Dicranum bergeri* 13 spp Sphagna including: *Sphagnum papillosum* *S. magellanicum* *S. rubellum* *S. cuspidatum* *S. imbricatum and* *S. fuscum.*
Rodwell (1991)	*Anemone nemorosa* *Campanula rotundifolia* *Danthonia decumbens* *Hypericum pulchrum* *Listera cordata* *Primula vulgaris* *Trientalis europaea* *Viola riviniana*	*Luzula multiflora*	*Lycopodium clavatum*	
Wigginton (1999)	*Genista pilosa* *Scheuchzeria palustris* *Tuberaria guttata*			
Stewart *et al*. (1994)	*Andromeda polifolia* *Arctostaphylos alpinus* *Orthilia secunda*		*Lycopodium annotinum*	
Preston *et al.* (2002)	*Arctostaphylos uva-ursi* *Juniperus communis* *Trientalis europaea*			
Page (1997)			*Blechnum spicant* *Lycopodium clavatum*	

For the most part the response of the vascular plants to burning on modified bog is a disturbance–induced response centred on the regeneration cycle of the most common dominant species, *Calluna*. JNCC notes that fire as a disturbance regime may be important but little research has been done other than for dry dwarf-shrub heaths (JNCC, 2009). At Dinnet Moor on Deeside, a dry heath habitat, a reduction in species richness with time after burning was shown (Hobbs and Gimingham, 1984a). In what these authors term “species-rich” heathland (17-29 species in the 0-25 year period), they reported a reduction in grass, forb and lichen growth. Indeed they reported little grass and forb regrowth in the older stands. In a similar study of burning on lichen diversity, also on heath vegetation (NVC Communities H10 and H12), the immediate effect of fire was to reduce lichen diversity, however, it recovered within 20 years, and thereafter declined (Davies and Legg, 2008), though changes were different for the different functional groups. Stands more than 25 years old generally had a lower diversity than stands 10-15 years old. Taken together, the results from these two chronosequences suggest that there is a flush of species in the immediate post-burn phase followed by a decline. These general conclusions have been corroborated by a recent multi-site study in the Peak District (Harris & Marrs, unpublished data). It is also worth noting that species richness is not always the same as species distinctiveness and that sites that have low species richness e.g. unburned areas, may have low number of species but these species are distinct and may fall under various priority designations. Those species that require longer rotations and are important for conservation purposes would need to be accounted for in any burning management plans and indeed many plans incorporate no burn areas (Natural England, pers. comm.). Delivering the range and variation in plant species may require a range of interventions on any particular moor.

Rotation lengths are extremely important as long vs. short rotation can have different effects on the ecosystem response (Hobbs and Gimingham, 1984a) and the pre-fire vegetation can affect the recovery of the vegetation and the community types following fire. Rawes and Hobbs (1979) investigated the effect of short and long term burning on blanket bog at the Moor House National Nature Reserve and found that *Calluna* regeneration from seed and by vegetative regrowth was greater in the short rotation plots. When combined with light grazing, *Rubus chamaemorus* was considerably more abundant in the short 10-year rotation burn compared either to the 20-year rotation or a vegetation allowed to recover for 50-years. This study was carried out from a heather management perspective. Nevertheless, this result is consistent with those of Hobbs & Gimingham (1984a) and Davies & Legg (2008).

It is also worth considering the impact of prescribed burning on *Calluna* recovery. This is entirely dependent on the mode of recovery of the *Calluna*, whether from seed or from vegetative means, or a combination of the two (Marrs, 1988). On deep peats or vegetation in the more oceanic parts of the UK there is likely to be regeneration from both resprouting and seed. Additionally, layering (adventitious rooting) of stems is another important regeneration method for *Calluna* (Macdonald et al., 1995; Scandrett and Gimingham, 1989). However, the ability of the *Calluna* to regenerate via resprouting reduces with age (Marrs, 1986; Marrs, 1988; Miller and Miles, 1970). The regeneration from seed will be a function of the severity of the fire; heat can stimulate germination but if too high can ignite the organic layer destroying the seed bank. Regeneration is also a function of the post-fire seed bed and low severity fires may leave behind layers of moss or litter that would provide limited opportunities for *Calluna* re-establishment

In lowland heaths in more continental climates, admittedly these will almost certainly be on podzols rather than peat, regeneration is mostly from seed (Marrs, 1986; Marrs, 1987; Marrs, 1988).

5.1.2 Fauna

Of the studies that investigate burning effects on peatland fauna, most have studied the impact on bird species. Table 5 shows some of the observed changes to bird populations with burning. For a comprehensive review see Pearce-Higgins et al. (2009) where much more detail can be found on bird numbers, density, breeding success and grouse moor management and vegetation cover. Burning appears to benefit some species e.g. Golden plover but at the detriment of others e.g. Meadow pipit. Grouse numbers have been correlated to prescribed burning (Section 4.4, Table 8). Studies that investigate the link between vegetation and birds find that most birds show an association for short open vegetation that would be produced through burning. However, it must be noted that it can be hard disentangling the effects of prescribed burning from that of estate management such as predator control and also the general effects of changes in vegetation architecture. Ongoing research at Langholm Moor Demonstration Project is attempting to address these issues.

Soil fauna such as Enchytraeid worms has been shown to play an important role in carbon cycling (Cole et al., 2002). However, increases (Mallik and FitzPatrick, 1996; Maltby and Edwards, 1984) and decreases (Brown, 1986) in soil fauna have been observed with burning.

Data on the effect of burning on invertebrates is equivocal; increases in spiders and beetles have been observed (Usher, 1992), but impacts on groups such as Lepidoptera (MacDonald and Haysom, 1997) such as the Large Heath butterfly (Dennis and Eales, 1997; Dennis and Eales, 1999) show both increases and decreases.

There are few data for mammals – only those grouse moor studies that also include species such as hares and rabbits (Hudson, 1992). Tucker (2003) suggests that burning practices that favour grasses at the expense of heather would lead to greater rabbit and vole populations. This is derived from their known habitat requirements. Mallon et al. (2003) concurs with Tucker's view of predicted rabbit numbers

Research into the effect of burning on stream biota has been noted to be lacking, however, Ramchunder et al. (2009) propose a conceptual model that hypothesises likely effects of prescribed burning on stream ecosystems and biota. They suggest that if prescribed burning is expected to increase suspended sediment, primary producers will be smothered, altering the balance between grazers e.g. mayflies (Heptageniidae), but increase in abundance of collector-filterers such as black fly larvae (Silmuliidae).

Table 4 *Effects of prescribed burning on the flora of peatlands*[6]

Author	**Bryophytes**	***Calluna vulgaris***	**Graminoids**	**Molinia caerulea**	**Vaccinium myrtillus**	**Floristic Diversity**
Ward et al. (2007)	↓		↑			
McVean & Ratcliffe (1962)	↓		↓			
Marrs et al. (2004)				×		
Rodwell (1991)						
Stewart et al. (2005)	↑					
Stewart et al. (2004a; 2004b)						↔
Hobbs & Gimingham (1984a)		↑ long rotations	↑ Eriophorum short rotations			
Tucker (2003)		↑ long rotations ®	↑ E. vaginatum short rotations	↑ short rotations ®	®	

® = rapid regeneration

[6] Attempts to impose a universal classification on these disparate studies has proved impossible

Table 5 *Effects of prescribed burning on the fauna of peatlands FAUNA*

Author	**Upland bird species**[7]						**Soil fauna**	**Invertebrates**	**Mammals**
	Golden Plover	Lapwing	Curlew	Meadow Pipit	Skylark	Whinchat			
Maltby and Edwards (1984)							↑		
Brown (1986)							↓		
Mallik and Fitzpatrick (1996)							↑		
Tharme et al. (2001)*†	↑	↑	↑	↓	×	×			
Whittingham et al. (2001)	↑								
Smith et al. (2001)				↓					
Thompson et al. (1997)									
Usher (1992)								↑	
MacDonald and Haysom (1997)								↔	
Dennis and Eales (1997; 1999)								↔	
Hudson* (1992)									↑

*** dealt with grouse moor management rather than burning *per se*** † arrows are for bird density see Pearce-Higgins et al (2009) for breeding success or population change

[7] Grouse are dealt with separately in Table 7 as part of the economic drivers of managed burning.

5.2 Hydrology

Burning can alter the hydrological status of a peatland through changes to the amount and nature of water flow and through changes to the water quality such as changes in pH.

5.2.1 Flow of water

Although there are several studies that detail the runoff responses following wildfires (e.g. DeBano, 2000; Doerr et al., 2006; Johansen et al., 2001) there are few studies that deal with runoff responses from prescribed burns. Greater amount of runoff and flashy hydrology have been associated with bare or eroded sites (Evans et al., 1999). These conditions may be present following burning which may lead to increases in runoff though Kinako and Gimingham (1980) have shown that erosion is limited to the first 2 year following burning through the re-establishment of vegetation. Of those that specifically look at prescribed burning and runoff occurrence, increases (Clay et al., 2009a) and no significant differences (Meyles, 2002) have been observed.

Rates of infiltration have been noted to change as a result of burning: Imeson (1971) suggested that rates increased (but did not actually measure them), whilst Mallik et al. (1984) found rates of infiltration decreased resulting in increased rates of erosion. The authors of the latter study suggested that this may be due clogging of ash in the pores, though this was not backed up with any definitive evidence and other explanations may be possible to explain the effect. Burning in other settings has been associated with the development of water repellency that limits infiltration (DeBano, 2000)**.** However, Mallik and Rahman (1985) demonstrated that water repellency in regularly burnt peat peaked within the first month after burning then declined to a minimum. Mallik and Fitzpatrick (1996) used thin section studies to show that porosity increased in recently, intentionally burnt soils but that any difference disappeared within 2-3 years of burning. They also noted that the pore size distribution changed towards smaller pores that they associated with increased activity of Enchytraeid worms (see also section 4.1.2).

Through burning, vegetation composition can be altered (Section 4.1), leading to the dominance of particular species such as *Molinia caerulea* or *Calluna vulgaris*. By shifting vegetation to *Calluna*-dominated communities hydrological properties can be altered. Holden (2005) shows that *Calluna* was associated with higher frequencies of soil piping. The rooting system of *Calluna* (and other woody plants) helps to preferentially channel flow in the upper layers of the peat.

By changing the dominant vegetation, rooting depths may be altered and consequently the rate of evapotranspiration could be affected. By altering the evapotranspiration rates water table depths may be altered, though further detailed work on vegetation types and water tables is needed. When discussing water table changes it is important to define the reference surface from which the measurement was taken; many peatland studies use the peat surface as this reference surface (e.g. Daniels et al., 2008)

Clay et al. (2009a) show that water tables were shallower i.e. closer to the surface on burnt plots, reflecting the dominance of graminoids and forbs such as Eriophorum. The deepest water tables were found on the unburnt plots which were dominated by mature to degenerate heather. Similar results were found by Worrall et al. (2007a). Clay et al., (2009a) ascribe their observations of water table to changes in the hydraulic conductivity of the peat under different management. In this instance, the hydraulic conductivity was the lowest on plots that had been burnt every 20 years. In contrast to this finding, Fisher (2006) found no significant difference in hydraulic conductivity with burning.

5.2.2 Water quality

For many, the issue of water quality is the most important question when investigating the impact of burning on ecosystem services. Some 70% of the UK's fresh water is sourced from upland catchments (Bonn et al., 2009b) and any management that negatively affects water quality and specifically colouration is likely to be in contravention of the Water Framework Directive (Anon, 2000; Bateman et al., 2006; Kallis and Butler, 2002)

There is a debate currently as to how burning affects the colour of water coming off peat covered catchments. Water colour is defined here as the amount of light absorbed at a particular wavelength for example at 400nm (Thurman, 1985). Section 4.3 details the impact of burning on DOC as part of carbon cycling process. Of those studies that investigate water colour, two show decreases, one shows increases and one shows no significant difference (Table 6). However, Clay et al. (2009b) whilst showing decreases in water colour found no significant difference between different burning rotations and DOC from those plots. This may suggest that the nature of the DOC has changed rather than its quantity.

Both increases (Allen, 1964) and decreases (Worrall et al., 2007b) in pH have been observed following burning. Given that many vegetation species and communities are sensitive to acidity gradients (e.g. Wheeler and Proctor, 2000), burning induced pH changes could have important impacts on post-fire vegetation succession.

The response of major metals and nutrients in soil water and runoff water varies depending on the species in question. Both Worrall and Adamson (2008) and Clay et al. (2010b) show increases and decreases following burning. Worrall and Adamson (2008) observe lower Ca, Na, Mg and PO_4^{3-} concentrations on burnt plots with only Al showing significantly higher concentrations on burnt plots. In the year following a prescribed burn Clay et al. (2010b) show significant increases in Fe, Na and K in soil water. Clay et al. (2010b) use these changes in water chemistry to investigate changes to source waters following burning. They found that following burning soil water becomes more soil water like and runoff water becomes more like rainwater. This partitioning of incoming rainwater may have important implications for runoff export from burnt catchments.

Table 6 *Effects of prescribed burning on the hydrology of peatlands*

Author	Water Table[8]	Runoff	Hydraulic conductivity	Water colour	pH	Metals	Nutrients
Clay et al. (2009a)	↑	↑	↓				
Clay et al. (2009b)				↓			
Clay et al. (2010b)						←→	
Worrall & Adamson (2008)						←→	↓
Worrall et al. (2007a)	↑			↓	↓		
Meyles (2002)		×					
Fisher (2006)			×				
Allen (1964)					↑		
Chapman et al. (in press)				×			
Yallop et al., (2008)				↑			
Battle & Golladay (2003)					↑		

[8] Where increases are recorded on the water table column, this means that water table is closer to the surface

5.3 Carbon and greenhouse gas balance

Vegetation change (driven by management practice) may have a strong impact on DOC production. Evidence is building from a number of sources that vegetation cover is a key driver of DOC concentrations. Much of this evidence has been compiled into one document by Armstrong et al. (in review) and is also reviewed in detail by (Lindsay, 2010). *Sphagnum* and *Molinia* seem to be associated with low concentrations while *Calluna* is associated with higher concentrations of DOC. Thus if management alters the vegetation cover of sites then this might alter the C fluxes in the long term, and especially the DOC flux.

There are, relative to some other components of the carbon cycle, a large number of studies of DOC concentrations associated with prescribed burning. However, these studies differ in their spatial and temporal scales as well as the particular pathways they consider. At the plot scale, Ward et al. (2007) and Clay et al. (2009b) found no significant difference in DOC concentrations in soil waters between burnt and unburnt sites while Worrall et al. (2007a) and Helliwell et al. (2010) showed a significant decrease in DOC concentration in soil water though the latter study is not a deep peat. Worrall et al. (2007a) and Ward et al. (2007) considered the same site and only considered burnt sites 9-10 years after a burn. Clay et al. (2009b) and Helliwell et al. (2010) consider changes after a burn and Clay et al. (2009b) considered pre-burn vs. post-burn. Clay et al. (2009b) is the only study to consider surface runoff and none of these studies considered stream water DOC concentrations in comparison to measured soil or surface runoff water.

At larger scales the effects of fire on DOC concentration appear to be less equivocal. Burns more than 4 yrs old, or those on soil types other than blanket peat, show no observed effect on humic DOC in catchment drainage (Yallop et al., 2008; Yallop & Clutterbuck, 2009; Chapman et al., 2010). In total or partly blanket peat catchments, however, there is a highly significant relationship between the area of new burn (typically <4 yrs old) on blanket peat and drainage humic DOC concentration (Yallop et al., 2008; Yallop & Clutterbuck, 2009). Using long-term trend analysis, Clutterbuck & Yallop (2010) showed that this relationship explains a much greater fraction of the increase in drainage DOC over the recent past than either increasing temperatures or declines in acid deposition. Furthermore of six catchments examined, only four experienced large increases in drainage humic DOC and only those four had seen significant increases in extent of new burn on blanket peat. The remaining two catchments showed no increase in burning on blanket peat and exhibited only small increases in drainage humic DOC. Yallop et al. (2010) show that increases in humic DOC concentrations related to new burns on blanket peat represent an increase in loss of carbon, and that areas of new burn (<4 yrs old) on blanket peat show a 5- to 15-fold greater loss of humic DOC compared to areas not burned that recently. Chapman et al. (2010) also note increases in DOC concentration but these were independent of burning and the variation in increase was larger than that observed by Clutterbuck and Yallop (2010).

Possibly most importantly, none of studies, plot-scale or catchment studies, have proposed a mechanism to link the plot-scale observation studies with catchment observations. This disconnect between the scales is an area of research that needs resolving. This range of observations is reflected in Table 7.

Table 7 *Studies investigating the relationship between prescribed burning and DOC production and export and range of scales and water types*

Study	Drainage DOC		Interstitial DOC		Surface flow DOC	
	New burn	Old Burn	New burn	Old Burn	New burn	Old Burn
Plot scale						
Ward et al. (2007)				×		
Worrall et al. (2007a)				↓		
Clay et al. (2009b)			×	×	×	×
Helliwell et al. (2010)			↓			
Catchment Scale						
Yallop and Clutterbuck (2009)	↑	×				
Clutterbuck and Yallop (2010)	↑	×				
Chapman et al. (in press)		×				
Yallop et al. (in press)	↑	×				

With regard to POC, no published study has direct information for POC fluxes from prescribed fire areas; Clay et al. (in press) used relative numbers based upon suspended sediment concentrations at the Hard Hill plots, Moor House (Clement, 2005) and showed that POC ranges from 11-38 mg l^{-1} on the experimental plots. In contrast, where wildfires occur then erosion losses have been shown to increase. Wildfires can burn deeper than well prescribed burns so that plant roots are killed leading to break up of the surface and physical erosion. They also tend to occur over much larger areas so erosion losses would be expected to be greater and to stand more risk of getting into water courses. There are many documented examples of extreme erosion associated with wildfire events (Maltby, 1980; Maltby et al., 1990; Tallis, 1997). Rapid erosion leads to very high POC export from the system and increases in suspended sediment loads could have important implications for diffuse pollution and strategic management of catchments e.g. River Basin Management Planning.

There are fewer studies of gaseous exchange on sites under prescribed burning. Ward et al. (2007) found increases in gross ecosystem CO_2 fluxes of both respiration and photosynthesis in burned and grazed treatments plots relative to controls. Clay et al. (in press) found significantly higher primary productivity on recently burnt sites in comparison to unburnt control sites.

Garnett et al. (2000) examined long-term experimental plots at Moor House, North Pennines, and found that burning reduces peat accumulation in comparison to no burning. Recalculating the data of Garnett et al. (2000) based upon all of their data, shows that the mean difference between burnt and unburnt treatments was 2.3 kg m^{-2} (not 2.48 as reported), this gives a mean effect of burning of 55 tonnes C km^{-2} yr^{-1} (not 73 tonnes C km^{-2} yr^{-1} as reported). Pietikäinen et al. (1999) working in Finnish mires determined that C sequestration at regularly burned sites was half that at unburned sites. The average C loss associated with a single fire was 2500 g C m^{-2}. Similarly, Kuhry (1994) used peat core data to demonstrate that rates of peat accumulation in Boreal Canada reduce with increased frequency of wildfires. However, these studies measure peat accumulation as a proxy for C accumulation. Clay et al. (in press) studied the Moor House plots further and showed that burnt sites were a mean source of approximately 117.8 g C m^{-2} yr^{-1} compared to unburnt sites with a mean source of 156.7 g C m^{-2} yr^{-1}.

Many of the above studies only consider one component of the carbon budget and, as such, cannot comment on the complete carbon budget. Therefore, using a meta-analysis approach, Worrall et al. (2010) combine results from existing studies and show that there are carbon benefits if prescribed burning ceased (Worrall and Bell, 2009; Worrall et al., 2010; Worrall et al., 2009). However, in the absence of any fuel management measures, there is a potential increase in fuel load and any subsequent wildfire could be more damaging and extensive such that it could cancel out any carbon gains

Many of these studies consider carbon fluxes or carbon stores in the peat soils and do not assess the carbon produced during fires in the form of char. The production of char, a refractory form of carbon (Preston and Schmidt, 2006), may have important implications for carbon cycling in peatlands due to the long mean residence time (Lehmann et al., 2008), and resistance to chemical agents (Bird and Gröcke, 1997). The amount of carbon produced during fires may be of the same order of magnitude as some carbon flux components of the complete carbon budget even though they are temporally intermittent inputs of carbon (Clay and Worrall, in press).

Assessing the amount of fuel consumed and char produced during prescribed fires has only recently been added to the complex debate about burning and carbon and consensus is still some way off (e.g. fuel consumption - Farage et al., 2010; Legg et al., 2010)

Fuel consumption during fires has been assessed though its implication in char formation has not been studied in much detail. No studies have been published that quantify the char production in prescribed burns but in Clay and Worrall (in press) the char production of a dwarf-shrub heath wildfire is calculated and shows that approximately 14% of the above-ground biomass survived the fire and that of that biomass combusted in the fire 4% was converted to char. Although this shows a high consumption of fuel it is also within the range of fuel consumption for prescribed burning (Legg et al., 2010). The amount of char produced in this fire falls within the range of black carbon produced in fire in other settings (Forbes et al., 2006). However, char production may vary with fire behaviour and the completeness of combustion which may be related the temperature and duration of the fire. Further work is ongoing in the analysis of char production during a series of prescribed burns in the Peak District (Worrall and Clay, unpublished data)

The aim of prescribed burning should be to create a quick moving fire that leaves behind a proportion of ‘stick’ (Defra, 2007a) without damaging the litter and underlying soil. Whilst there has been much discussion on what constitutes a ‘cool’ burn and the extent to which it is practised (Davies et al., 2010; Reed et al., 2009a), a well managed burn would perhaps be expected to leave behind a greater proportion of biomass and leave critical layers such as peat forming Sphagnum mosses undamaged. Indeed a range of fuel consumptions from <30 to 100% for prescribed burning has been recorded (Farage et al., 2009; Kayll, 1966; Legg et al., 2010). In leaving unburnt and/or dead biomass following the fire, this is an additional carbon stock that needs to be accounted for when assessing the carbon impact of burning.

Finally, a note of caution is needed when reviewing the impacts of burning on carbon and greenhouse gases. The variety of locations and scales of studies make overall generalisations difficult. Plot scale studies have shown different results to those at a catchment scale, particularly on the issue of DOC. These contrasting results may not be completely at odds with each other as processes between production site and catchment outlet may alter the quantity and quality of the DOC exported. Sources may be different as scale increases from plot to catchment; or sites may simply be distinct in the change that burning makes.

Table 8 *Effects of prescribed burning on the carbon dynamics of peatlands*

Author	Soil Respiration	Primary productivity	Methane	DOC[9]	POC	Dissolved CO_2
Ward et al. (2007)	↑	↔	↓	×		
Worrall et al. (2007a)				↓		
Ball (1974)		↔				
Garnett et al. (2000)		↔				
Clay et al. (2009b)				×		
Imeson (1971)		↓			↑	
Tallis (1987)					↑	↑
Mitchell and Macdonald (1995)					↑	
Clay et al. (in press)	×	↑	↑[10]	×	↑[11]	×
Clement (2005)					↑	
Yallop and Clutterbuck (2009)				↑		

5.4 Socio-economic impacts

Prescribed burning in the uplands of the UK has well defined production exports e.g. grouse and sheep production, but also a wider social impact. This wider impact is often hard to quantify as it includes many intangible benefits such as landscape aesthetics.

5.4.1 Grouse production

Positive impacts have been observed in many studies of prescribed burning and grouse production (Table 9) and have been observed for many years (Picozzi, 1968). This may not be surprising as prescribed burning seeks to optimize habitats for grouse populations so increase in numbers or survival are likely to be observed. However, it must be noted that many of the studies that show positive outcomes (e.g. Tharme et al., 2001) investigate grouse moor management and do not study prescribed burning in isolation. Factors such as predator control are included in the management which makes it hard to separate out the effect of burning alone.

There is evidence that climate change is leading to changes in the timing of breeding and possibly diet in some peatland birds (National Ecosystem Assessment, in press). Climate change may interact with other drivers of change to affect grouse populations in unpredictable ways, for example a combination of sheep grazing and acid deposition provide the best explanation for the expansion of grasses into bog habitats (Van der Wal et al., 2003), which combined with climate change may influence the abundance of heather beetle (Rosenburgh and Marrs, 2010) leading to further habitat loss for grouse. Climate change may also increase the abundance of ticks at high altitudes (Gilbert, 2010), with effects on red grouse and hill sheep.

5.4.2 Livestock production

There has been limited published works that directly investigate the impact of burning on sheep production (Table 9). In one of the few works Lance (1983) observed enhanced sheep performance (15% greater lamb production and 32% greater liveweight production) with burning. The author points out that this is a single experiment and may not be representative of

[9] Water colour (absorbance at defined wavelengths) is often used as a proxy for DOC but the data on this has been summarised in the Table 5
[10] Not directly measured, based on water table record
[11] Based on Clement (2005)

other soil or vegetation types. There are other studies that investigate the interaction between grazing and prescribed burning and have shown that Burnt area tend to be more heavily grazed (e.g. Miles, 1971) and that grazing, in particular heavy grazing, can keep dwarf shrubs such as *Calluna* short (Grant, 1971; Grant and Hunter, 1968).

There are also anecdotal accounts that sheep distribution, and hence grazing utilisation of the moor, is enhanced in a moor that is actively burned. Where burning is not used the vegetation can become impenetrable to sheep. However, bog vegetation may not be very productive for livestock and conservation stocking rates for bog and bog restoration are very low. Sheep are not the only grazer in these settings, for example, cattle and deer production, but there are few available published studies on prescribed burning and these grazers.

With both livestock and grouse production there are few studies that attempt to quantify the economic activity associated with the production of grouse and sheep. Grouse moors support many jobs directly, i.e. gamekeepers, but also many secondary jobs e.g. local bed and breakfasts. McGilvray (1995) calculated grouse shooting provided £14.7 million in wages in Scotland in the early 1990s and it supported 904 full-time jobs in the hotel industry. The larger sporting shooting industry has been calculated to be worth £1.6 billion to the UK economy, with 12% or £120 million, spent on grouse-shooting in good grouse years (PACEC, 2006). Gardner et al. (2009) show that much of upland hill farming for sheep or cattle is under-pinned by subsidies such as Higher Level Scheme (HLS) and Hill farm Allowance (HFA)

5.4.3 Landscape value and perceptions

Whilst surveys are commonly used in assessing perceptions of uplands areas such as National Parks (e.g. Peak District National Park Visitor Survey, 2005; Suckall et al., 2009), there are few studies from the UK that specifically look at the public's perceptions of prescribed burning. These kind of studies are commonly conducted in USA and Australia especially in fire prone ecosystems (Bell and Oliveras, 2006; Vining and Merrick, 2008). Here the aim is to understand perceptions of prescribed burning as a method for reducing wildfire intensity/frequency.

5.5 Wildfire

Prescribed burns and wildfire are both part of the UK fire regime and interlinked processes (McMorrow et al., 2010). Where degraded peatlands are dominated by *Calluna*, prescribed burning consumes older heather and allows new growth and regeneration. Through this process fuel loads may be reduced so that wildfires are limited or even suppressed. This school of thought has long been thought as a beneficial by-product of prescribed burning for grouse or sheep. However, little empirical research (Table 9) has been conducted to show how prescribed burning interacts with wildfire – does prescribed burning reduce the likelihood of ignition, fire intensity or fire frequency? McMorrow et al. (2009) show a low empirical risk of wildfires on heather moor which they suggest may be due to prescribed fires reducing subsequent fuel load for later wildfires.

The risk of prescribed burns becoming wildfires has also received little attention. The Peak District National Park ranger reports between 1976 and 2004 record 341 wildfires. Of the 341 reported wildfires, 41 have an attributed cause and of those 41, ten have been attributed to prescribed burns, i.e. a little under 25% of wildfires with a known cause are due to prescribed burning. However, when the area of the wildfires is considered of the 41 fires with an assigned cause, those due to prescribed burns represented 51% of the burnt area, i.e. fires from prescribed burns appear to have been bigger when they did occur.

There are data quality issues surrounding the recording of vegetation fires in the UK which makes any analysis difficult. Before the introduction of the Incident Recording System (IRS) in the UK, Fire and Rescue Services often had a “favourite” attributed cause which varied over time (Walker et al., 2009)

When considering the relative pros and cons surrounding prescribed burning and wildfire, there is an element of making a trade off over longer timescales: for example what is the cumulative impact of prescribed burning on a 10 year rotation over 50 years versus a wildfire on a no burn area with a return period of 50 years. To date this kind of assessment has not been done.

There is also a counter-balancing argument that prescribed burning encourages a fire-adapted ecosystem whereas the absence of burning could lead to a wet bog ecosystem that is more fire-resilient. Given that many of the UK peatlands are not under grouse moor style burning, other management strategies need to be investigated in order to manage any risks from wildfire. These could include partnership working, sharing of resources, creation of fire breaks and increased communication with the public regarding fire risk and closure of sensitive areas.

Table 9. *Effects of prescribed burning on some socio-economic activities of peatlands*

Author	**Sheep production**	**Grouse numbers**	**Wildfire**
Picozzi (1968)		↑	
Lance (1983)	↑		
McMorrow et al. (2009)			↓
Tharme et al. (2001)*		↑	
Hudson (1992)		↑	
Lovat (1911)		↑	
Miller et al. (1966)		↑	

*** dealt with grouse moor management rather than burning *per se***

6. Practical tools for monitoring and assessment of prescribed burning

Practical monitoring and assessment can operate at a range of scales and for a variety of end-points. Remote sensing techniques including aerial photography (Yallop et al., 2006b) and hyper spectral imaging (McMorrow et al., 2004) have shown their potential for monitoring at the national or regional scale and allow for area of burning and age of burn to be assessed. This scale of monitoring can only be interpreted by the aid of well characterised individual burn sites of known history.

For assessing the impact of burn management at the individual burn scale a range of techniques have been employed including:

- Quadrat surveys (e.g. Price et al., 2003)
- Birds number counts

- Dipwells (e.g. Worrall et al., 2007a)
- Carbon (including charcoal) stock accounting (Clay and Worrall, in press)

However, there is no one single measure or proxy by which the impacts of burn management on ecosystem services can be assessed.

7. Good Practice, potential for policies to encourage good management practice and alternatives to burning

This review has covered some of existing evidence base in relation to prescribed burning on UK peatlands. The next step is to translate this into practical guidance to land owners and managers to implement on the ground. Whilst it is out of the scope of this review to advise on a definitive policy and practice it is worth asking some questions of what we mean by good practice and ways by which policy can encourage this.

The key question to ask is what is meant by good practice and what does it mean to different stakeholders? Good practice could be defined as maintaining or altering current management practice such that there is the potential to improve delivery of one or multiple ecosystem services i.e. where and when is burning appropriate.

Given the mixed evidence for the effects of burning on the provision of different ecosystem services in different contexts, it is difficult to make firm recommendations about good practice, and what may encourage better burning practice. With reference to ecosystem services in this review, managed burning has been shown to bring benefits, neutral effects and harmful actions to UK peatlands. The literature on managed burning primarily covers studies that focus on the presence or absence of a particular ecosystem service so that any changes to the *style* of burning e.g. rotation length or technique, is not covered. It follows, therefore that there is a large gap in the literature regarding best possible practice to optimise multiple ecosystem services.

Prescribed burning on peatlands in the UK is regulated by a series of regulations (see Table 1) and supported by guidance issued in the Heather & Grass Burning Codes (Defra, 2007a; Welsh Assembly Government, 2008) and in the Muirburn Code (SEERAD, 2008) in Scotland. The regulations set out the season when burning may take place and guidance for carrying out burning safely and effectively. Separate organisations consider burning in the different parts of the UK and there is little communication between the groups (see IUCN Technical Review no. 8).

The Science Panel commissioned by Defra in 2005 to investigate evidence for the need to introduce changes to the Heather & Grass Burning Regulations and Code concluded that there was no evidence to support any major changes to the code (Glaves and Haycock, 2005). However there now appears to be conflicting evidence about the current burning seasons. In Wales, the 2008 review of the Heather & Grass Burning Regulations shortened the burning season so that it ended on 31 March, rather than 15 April. This change is being considered in the other parts of the UK in order to protect breeding birds, although currently there is no conclusive evidence that this would beneficial. Practitioners argue that a shortening of the season will reduce their opportunity to carry out the burning required to manage their moorland areas as often the only time that burning is possible is during April.

The predictions of warmer and wetter winters may bring into doubt the ability to complete the planned heather burning programmes and this could leave the areas with drier peat, which have a higher proportion of heather, at greater risk of damage from wildfires. Summer wildfires are likely to be hotter and have a greater risk of burning into the peat and destroying it. These fires are difficult and expensive to control and as a means of coordinating resources this risk has encouraged the formation of Fire Groups throughout the country, often led by the local Fire & Rescue Services (Technical Review no. 8).

Technical Review no. 8 considers a range of policy instruments that could facilitate sustainable peatland management, some of which could be used to alter the extent of prescribed burning in future. Options considered include creating markets to pay for peatland ecosystem services, information provision, capacity building, market incentives, classic regulation and state control. Capacity building in this context may include training in burning skills, as recommended in Defra's (2007b) response to their consultation on the review of the Heather & Grass Burning Code. Although state control would not be appropriate in most British peatlands due to current patterns of land tenure, greater regulation of prescribed burning may be possible through more stringent rules and penalties. A number of organisations are in favour of turning the current guidelines into more enforceable and restrictive regulation. However, DEFRA opted to retain and adapt the Heather & Grass Burning Code, and more regulation of managed burning is unlikely in the near future. This may however need to be reviewed if clearer evidence emerges of the link between managed burning and dissolved organic carbon (DOC), given that this may in future incur penalties under the Water Framework Directive.

The use of incentives via existing agri-environmental schemes or the creation of new markets for ecosystem services (such as carbon) affected by prescribed burning (such as for carbon and water, if a clear link between burning, carbon dynamics and water quality can be demonstrated in future) may be the most economically efficient way of achieving widespread behavioural change.

Burning practices may also be influenced by other drivers of change, where these lead to a contraction in the area of peatland managed for game. Broadly speaking, there are two sets of scenarios that may lead to this (Reed et al., 2009b). On one hand, further extensification of land use and management in peatlands, with a focus on wildlife and carbon management, and perhaps including a ban on shooting wild birds, may lead to the abandonment of some of the more remote peatlands and a partial reforestation of the drier areas. On the other hand, an intensification of land use and management in peatlands, perhaps in response to future demands for self-sufficiency in food, may see more intensive livestock systems and arable agriculture replacing land that was formerly managed for game, with a subsequent reduction in managed burning. As such, burning policies will need to adapt to changing future contexts.

If we are to discuss good practice with respect to burning we must also consider whether there are alternatives that would have the same or improved utility but with reduced risks to ecosystem services. There are two alternatives to burning. Firstly, rather than reducing vegetation by fire it can be removed by grazers consuming it. However, *Calluna* is not always a preference food for sheep and cattle preferring rather grasses and sedges such as *Eriophorum spp*. (Grant et al., 1987), though this can vary and is influenced by factors such as patch size and slope (Hester et al., 1999). Grazers bring associated risk of overgrazing leading to soil erosion and compaction of soils (Willatt and Pullar, 1984). The only practical use of grazers to control shrubby vegetation would be when the vegetation is young. The second possible alternative to burning for the control of vegetation would be the use of cutting or mowing.

Cutting or mowing can be done with or without lifting the cut material. Cutting or mowing have several possible disadvantages: cutting requires more access to more machinery than required by burning, especially if the cut vegetation is being removed from the site; the machinery will have a high impact on the peat leading to over-compaction.

We do not consider that use of herbicides would ever be a practical single technique for vegetation control on peatlands though it may be used in conjunction with burning e.g. glycophate pre-treatment to burning. It is of course possible that in landscape a range of techniques for vegetation control could be used, for example, cutting near road access but burning where access is more limited.

8. Missing data and future work

Following each of the major reviews over the last 10 years into the impacts of prescribed burning (Glaves and Haycock, 2005; Gray and Levy, 2009; Tucker, 2003) many research priorities were identified and questions posed. Table 10 details the key themes from these reviews and asks whether the original question has been answered. In most instances the answer is no, but recent and ongoing research in some areas has moved the understanding on to some degree in some areas. The table also details examples of research that has been conducted since the major reviews and any ongoing projects that have yet to report their data

As can be seen by addressing one area of research new questions arise out of this. For example, several studies into carbon and burning have been conducted since the major reviews adding information to the debates but have not yet given conclusive results. Many studies focus on single elements of the carbon balance and only one study examines a full carbon budget of a prescribed burn site (Clay et al., in press). However, even this study has its caveats. It was conducted on a small scale plot experiment in the North Pennines on a pristine site (Moor House) which is unlikely to compare with many sites around the UK e.g. the degraded peats of the Peak District. Indeed Gray and Levy (2009) question the transferability of Moor House results to other parts of the country. Some of the other works reviewed in this paper also come from the Hard Hill plots at Moor House. Additionally, many of the works reviewed come from marginal habitats and peatlands leading to questions about the scaling of results across the UK and its devolved administrations.

Additional questions have also arisen out of this carbon work such as the intensity of the burns themselves - where they more or less intense? Some initial work from ongoing studies in Northumberland and the Peak District suggests that the nature of the burn may dictate later carbon fluxes rather than the time since it was carried out (Worrall and Clay, unpublished data) making the question of spatial heterogeneity an important one.

Many studies presented in this review do not qualify the nature of the fire itself and the fire regime present in that area that leads to difficulties when trying to draw general conclusion. This latter point is important when assigning control sites in “unburnt” vegetation. In most areas managed by fire, these “unburnt” areas are likely to have been burnt at some point, perhaps unknowable, in the past. Therefore, a key message must be that we need a greater amount of long-term monitoring if we are to avoid short-termism

Additionally the issue of standardised terminology was raised during the review process and at the IUCN Peatland Conference in Durham September 2010. If meaningful conclusions are to be drawn from the masses of work ongoing, uniform terminology and methodologies needs to be drawn up *and* used.

The establishment and funding of national demonstration sites via an independent body may assist in dealing with current gaps, past inconsistencies and reduce these in future work.

Table 10 *Key questions still to be answered at the end of the major reviews over the last decade with additional questions from an IUCN Stakeholder workshop in July 2010. Questions are not necessarily direct quotes and may be paraphrased to combine several similar questions. NB. It may be that there are ongoing projects not covered in this table; if any have been missed, please contact IUCN in order for this table to be updated.*

Question Posed/ Further research required	**Reference(s)**	**What data is available on this question?**	**Are there any ongoing projects that are addressing this topic?**
General questions			
What are the effects of repeated (serial) burning?	(Gray and Levy, 2009) (MacDonald, 2008)	Hard Hill plots only experiment with long term *repeated* burns	
A specific review into burning in lowland habitats	(Glaves and Haycock, 2005)		
What is the geographical extent of research into prescribed burning?		A mapping exercise would be required for this.	
Ecological			
How does burning affect peat forming species, in particular Sphagnum (all 30 species)?			
How does Sphagnum recover from burning	(MacDonald, 2008; Tucker, 2003)		
How does prescribed burning impact birds communities	(Glaves and Haycock, 2005; Tucker, 2003)	(Fletcher et al., 2010)	Upland predation experiment, GWCT
What is the optimal patchwork of burning within grouse territories?			
How does burning affect invertebrate communities?	(Hobbs and Gimingham, 1987; Tucker, 2003)		EMBER
Fire behaviour			
How does the interaction between grazing and prescribed fire impact peatlands?	(Glaves and Haycock, 2005; Gray and Levy, 2009; Hobbs and Gimingham, 1987; Tucker, 2003)	(Grant and Hunter, 1968)	Hard Hill plots
What are the environmental conditions e.g. weather, topography, under which burning can be carried out safely	(MacDonald, 2008)		Northumberland field burns – Fire Research Centre, Manchester University

What is the impact of variable fire behaviour on ecosystem services?	(Glaves and Haycock, 2005)		
How does prescribed fire affect and interact with wildfire?	(Glaves and Haycock, 2005; Gray and Levy, 2009; Tucker, 2003)	Limited at best	
Impact of fire on major cycles in peatlands			
What is the impact of burning on nutrient cycling	(Hobbs and Gimingham, 1987; Tucker, 2003)		FIREMAN;
What are the effects of burning on peatland carbon cycle processes?	(Glaves and Haycock, 2005; Gray and Levy, 2009) (MacDonald, 2008)	(Clay et al., 2009b; Clay et al., in press; Ward et al., 2007; Worrall et al., 2007a; Yallop and Clutterbuck, 2009)	EMBER Otterburn project, GWCT and Durham University
An assessment of erosion and hydrological impacts of fires	(Glaves and Haycock, 2005; Tucker, 2003)	(Clay et al., 2009a)	EMBER project
Societal benefits of burning			
What are the social consequences of using prescribed fire in peatlands	(Gray and Levy, 2009)	Moorland association survey	Aberdeen projects
An assessment of current (and historic) burning practices	(Davies, 2008; Glaves and Haycock, 2005; Tucker, 2003)	(Yallop et al., 2006b)	

9. Conclusions and key messages

- Prescribed burning has been shown to bring benefits for some ecosystem services.
- Equally, prescribed burning has been shown to bring dis-benefits or at best neutral.
- There is a gap in the literature surrounding burn management practice that makes it difficult to recommend changes in individual styles of burning or management.
- Knowledge gaps include:
    - The range of burn practice across the UK
    - Does prescribed burning prevent wildfire?
    - The direct link between an ecosystem service and the style of management e.g. grouse production, sheep production, and water quality.
- Particular concerns remain around the provision of certain ecosystem service from peatlands that this review was unable to resolve e.g. water quality (DOC).

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References

ADAS, 1997. Biological monitoring of moorland in the North Peak ESA 1988-1996, MAFF, London.
Allen, S.E., 1964. Chemical aspects of heather burning. Journal of Applied Ecology, 1: 347-367.
Anon, 2000. Directive 200/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. Official Journal L 327/1.
Armstrong, A., Holden, J., Luxton, K. and Quinton, J.N., in review. Peatland vegetation type - a key driver of DOC? Science of the Total Environment.
Averis, A., Averis, B., Birks, J., Horsfield, D., Thompson, D. and Yeo, M., 2005. An Illustrated Guide to British Upland Vegetation. JNCC, London.
Ball, M.E., 1974. Floristic Changes on Grasslands and Heaths on the Isle of Rhum after a Reduction or Exclusion of Grazing. Journal of Environmental Management, 2(4): 299-318.
Bateman, I.J., Brouwer, R., Davies, H., Day, B.H., Deflandre, A., Di Falco, S., Georgiou, S., Hadley, D., Hutchins, M., Jones, A.P., Kay, D., Leeks, G., Lewis, M., Lovett, A.A., Neal, C., Posen, P., Rigby, D. and Turner, R.K., 2006. Analysing the agricultural costs and non-market benefits of implementing the Water Framework Directive. Journal of Agricultural Economics, 57(2): 221-237.
Battle, J. and Golladay, S.W., 2003. Prescribed fire's impact on water quality of depressional wetlands in southwestern Georgia. American Midland Naturalist, 150(1): 15-25.
Bell, T. and Oliveras, I., 2006. Perceptions of prescribed burning in a local forest community in Victoria, Australia. Environmental Management, 38(5): 867-878.
Bird, M.I. and Gröcke, D.R., 1997. Determination of the abundance and carbon isotope composition of elemental carbon in sediments. Geochimica et Cosmochimica Acta, 61(16): 3413-3423.
Bonn, A., Allott, T., Hubacek, K. and Stewart, J. (Editors), 2009a. Drivers of Environmental Change in Uplands. Routledge, London and New York.
Bonn, A., Allott, T., Hubacek, K. and Stewart, J., 2009b. Introduction. Drivers of change in upland environments: concepts, threats and opportunities. In: A. Bonn, T. Allott, K. Hubacek and J. Stewart (Editors), Drivers of Environmental Change in Uplands. Routledge, London and New York, pp. 1-10.

Brown, R.W., 1986. The effect of controlled burning and season on moorland soil fauna. Moorland Management, 2nd Report on the Moorland Management Programme., North York Moors National Park, Helmsley.

Burch, J., 2008. The relationship of bryophyte regeneration to heather canopy height following moorland burning on the North York Moors. Journal of Bryology, 30: 208-216.

Chambers, F.M., Mauquoy, D., Gent, A., Pearson, F., Daniell, J.R.G. and Jones, P.S., 2007. Palaeoecology of degraded blanket mire in South Wales: Data to inform conservation management. Biological Conservation, 137(2): 197-209.

Chapman, P., McDonald, A., Tyson, R., Palmer, S., Mitchell, G. and Irvine, B., in press. Changes in water colour between 1986 and 2006 in the headwaters of the River Nidd, Yorkshire, UK. Biogeochemistry.

CIFFC, 2002. The 2002 Glossary of forest fire management terms. Available online at http://www.env.gov.bc.ca/esd/fire_mgmt_gloss_2002.pdf. Accessed 15th July 2010. Canadian Interagency Forest Fire Centre, Winnipeg, Canada.

Clay, G.D., Bonn, A., Evans, M.G., Hewson, W., Parnell, M., Wilkinson, R. and Worrall, F., 2010a. Grindsbrook Wildfire 2008 - a case study. Moors for the Future Report., Moors for the Future Partnership, Edale.

Clay, G.D. and Worrall, F., in press. Charcoal production in a UK moorland wildfire - how important is it? Journal of Environmental Management.

Clay, G.D., Worrall, F., Clark, E. and Fraser, E.D.G., 2009a. Hydrological responses to managed burning and grazing in an upland blanket bog. Journal of Hydrology, 376(3-4): 486-495.

Clay, G.D., Worrall, F. and Fraser, E.D.G., 2009b. Effects of managed burning upon dissolved organic carbon (DOC) in soil water and runoff water following a managed burn of a UK blanket bog. Journal of Hydrology, 367(1-2): 41-51.

Clay, G.D., Worrall, F. and Fraser, E.D.G., 2010b. Compositional changes in soil water and runoff water following managed burning on a UK upland blanket bog. Journal of Hydrology, 380(1-2): 135-145.

Clay, G.D., Worrall, F. and Rose, R., in press. Carbon budgets of an upland blanket bog managed by prescribed fire. Journal of Geophysical Research - Biogeosciences.

Clement, S., 2005. The future stability of upland blanket peat following historical erosion and recent re-vegetation. PhD Thesis, University of Durham, Durham.

Clutterbuck, B. and Yallop, A.R., 2010. Land management as a factor controlling dissolved organic carbon release from upland peat soils 2: Changes in DOC productivity over four decades. Science of the Total Environment, 408(24): 6179-6191.

Cole, L., Bardgett, R.D., Ineson, P. and Adamson, J.K., 2002. Relationships between enchytraeid worms (Oligochaeta), climate change, and the release of dissolved organic carbon from blanket peat in northern England. Soil Biology & Biochemistry, 34(5): 599-607.

Coulson, J.C., Fielding, C.A. and Goodyear, S.A., 1992. The management of moorland areas to enhance their nature conservation interest. JNCC Reports, No. 134, Joint Nature Conservation Committee, Peterborough.

Daniels, S.M., Agnew, C.T., Allott, T.E.H. and Evans, M.G., 2008. Water table variability and runoff generation in an eroded peatland, South Pennines, UK. Journal of Hydrology, 361(1-2): 214-226.

Davies, A., 2008. Review of the historical environmental changes in the UK uplands relevant to management and policy, Economic and Social Research Council (ESRC), Swindon.

Davies, G.M. and Legg, C.J., 2008. The effect of traditional management burning on lichen diversity. Applied Vegetation Science, 11(4): 529-538.

Davies, G.M., Legg, C.J., Smith, A.A. and MacDonald, A.J., 2009. Rate of spread of fires in Calluna vulgaris-dominated moorlands. Journal of Applied Ecology, 46(5): 1054-1063.

Davies, G.M., Smith, A.A., MacDonald, A.J., Bakker, J.D. and Legg, C.J., 2010. Fire intensity, fire severity and ecosystem response in heathlands: factors affecting the regeneration of Calluna vulgaris. Journal of Applied Ecology, 47(2): 356-365.
DeBano, L.F., 2000. The role of fire and soil heating on water repellency in wildland environments: a review. Journal of Hydrology, 231: 195-206.
Defra, 2007a. The Heather and Grass Burning Code (2007 Version), Defra, London.
Defra, 2007b. Public consultation on the Heather and Grass Burning Regulations and Code - summary of responses. Unpublished report. Defra.
Defra, 2010. Assembling UK wide data on soil carbon (and greenhouse gas) in the context of land management. Project SP0567.
Dennis, R.L.H. and Eales, H.T., 1997. Patch occupancy in Coenonympha tullia (Muller, 1764) (Lepidoptera: Satyrinae): Habitat quality matters as much as patch size and isolation. Journal of Insect Conservation, 1(3): 167-176.
Dennis, R.L.H. and Eales, H.T., 1999. Probability of site occupancy in the large heath butterfly Coenonympha tullia determined from geographical and ecological data. Biological Conservation, 87(3): 295-301.
Dodgshon, R.A. and Olsson, G.A., 2006. Heather moorland in the Scottish Highlands: the history of a cultural landscape, 1600-1880. Journal of Historical Geography, 32(1): 21-37.
Doerr, S.H., Shakesby, R.A., Blake, W.H., Chafer, C.J., Humphreys, G.S. and Wallbrink, P.J., 2006. Effects of differing wildfire severities on soil wettability and implications for hydrological response. Journal of Hydrology, 319(1-4): 295-311.
Ellis, C.J., 2008. Interactions between hydrology, burning and contrasting plant groups during the millennial-scale development of sub-montane wet heath. Journal of Vegetation Science, 19(5): 693-U57.
Evans, M., Warburton, J. and Yang, J., 2006. Eroding blanket peat catchments: Global and local implications of upland organic sediment budgets. Geomorphology, 79(1-2): 45-57.
Evans, M.G., Burt, T.P., Holden, J. and Adamson, J.K., 1999. Runoff generation and water table fluctuations in blanket peat: evidence from UK data spanning the dry summer of 1995. Journal of Hydrology, 221(3-4): 141-160.
Farage, P., Ball, A., McGenity, T.J., Whitby, C. and Pretty, J., 2009. Burning management and carbon sequestration of upland heather moorland in the UK. Australian Journal of Soil Research, 47(4): 351-361.
Farage, P., Ball, A.S., McGenity, T.J., Whitby, C. and Pretty, J., 2010. Reply to Comment on: 'Burning management and carbon sequestration of upland heather moorland in the UK'. Australian Journal of Soil Research, 48(1): 104-104.
Fisher, K., 2006. The effect of controlled rotational heather burning on infiltration and hydraulic conductivity on an upland blanket peat, University of Leeds.
Fletcher, K., Aebischer, N.J., Baines, D., Foster, R. and Hoodless, A.N., 2010. Changes in breeding success and abundance of ground-nesting moorland birds in relation to the experimental deployment of legal predator control. Journal of Applied Ecology, 47(2): 263-272.
Forbes, M.S., Raison, R.J. and Skjemstad, J.O., 2006. Formation, transformation and transport of black carbon (charcoal) in terrestrial and aquatic ecosystems. Science of the Total Environment, 370(1): 190-206.
Fyfe, R.M., Brown, A.G. and Rippon, S.J., 2003. Mid- to late-Holocene vegetation history of Greater Exmoor, UK: estimating the spatial extent of human-induced vegetation change. Vegetation History and Archaeobotany, 12(4): 215-232.
Gardner, S.M., Waterhouse, T. and Critchley, C.N.R., 2009. Moorland management with livestock. In: A. Bonn, T.E.H. Allott, K. Hubacek and J. Stewart (Editors), Drivers of Environmental Change in Uplands. Routledge, London and New York, pp. 186-208.

Garnett, M.H., Ineson, P. and Stevenson, A.C., 2000. Effects of burning and grazing on carbon sequestration in a Pennine blanket bog, UK. Holocene, 10(6): 729-736.

Gilbert, L., 2010. Altitudinal patterns of tick and host abundance: a potential role for climate change in regulating tick-borne diseases? Oecologia 162: 217-225.

Glaves, D.J. and Haycock, N.E., 2005. Science Panel Assessment of the Effects of Burning on Biodiversity, Soils and Hydrology. Report to Defra Conservation, Uplands and Rural Europe Division, Uplands Management Branch.

Grant, S.A., 1971. Interaction of grazing and burning on heather moors. 2. Effects on primary production and level of utilization. Grass and Forage Science, 26(3): 173-182.

Grant, S.A. and Hunter, R.F., 1968. Interaction of Grazing and Burning on Heather Moors and their Implication in Heather Management. Journal of the British Grassland Society, 23(4): 285-293.

Grant, S.A., Torvell, L., Smith, H.K., Suckling, D.E., Forbes, T.D.A. and Hodgson, J., 1987. Comparative Studies of Diet Selection by Sheep and Cattle: Blanket Bog and Heather Moor. Journal of Ecology, 75(4): 947-960.

Gray, A. and Levy, P., 2009. A review of carbon flux research in UK peatlands in relation to fire and the Cairngorms National Park. CEH Project No: C03530, Centre for Ecology and Hydrology, Edinburgh.

Hamilton, A., 2000. The characteristics and effects of management fire on blanket bog vegetation in north-west Scotland. PhD Thesis,, University of Edinburgh, Edinburgh.

Helliwell, R., Britton, A., Gibbs, S., Fisher, J. and Potts, J., 2010. Interactive Effects of N Deposition, Land Management and Weather Patterns on Soil Solution Chemistry in a Scottish Alpine Heath. Ecosystems, 13(5): 696-711.

Hester, A.J., Gordon, I.J., Baillie, G.J. and Tappin, E., 1999. Foraging behaviour of sheep and red deer within natural heather grass mosaics. Journal of Applied Ecology, 36(1): 133-146.

Hester, A.J. and Sydes, C., 1992. Changes in burning of Scottish heather moorland since the 1940s from aerial photographs. Biological Conservation, 60(1): 25-30.

Hobbs, R.J., 1984. Length of Burning Rotation and Community Composition in High-Level Calluna-Eriophorum Bog in Northern England. Vegetatio, 57(2-3): 129-136.

Hobbs, R.J. and Gimingham, C.H., 1984a. Studies on Fire in Scottish Heathland Communities .2. Post-Fire Vegetation Development. Journal of Ecology, 72(2): 585-610.

Hobbs, R.J. and Gimingham, C.H., 1984b. Studies on Fire in Scottish Heathland Communities. 1. Fire Characteristics Journal of Ecology, 72(1): 223-240.

Hobbs, R.J. and Gimingham, C.H., 1987. Vegetation, Fire and Herbivore Interaction in Heathland Advances in Ecological Research, 16: 87-173.

Holden, J., 2005. Piping and woody plants in peatlands: Cause or effect? Water Resources Research, 41(6): 10.

Holden, J., Shotbolt, L., Bonn, A., Burt, T.P., Chapman, P.J., Dougill, A.J., Fraser, E.D.G., Hubacek, K., Irvine, B., Kirkby, M.J., Reed, M.S., Prell, C., Stagl, S., Stringer, L.C., Turner, A. and Worrall, F., 2007. Environmental change in moorland landscapes. Earth-Science Reviews, 82(1-2): 75-100.

Hudson, P.J., 1992. Grouse in Space and Time: The Population Biology of a Managed Gamebird. Game Conservancy, Fordingbridge.

Imeson, A.C., 1971. Heather Burning and Soil Erosion on North Yorkshire Moors Journal of Applied Ecology, 8(2): 537-&.

JNCC, 2009. Common Standards Monitoring Guidance for Upland Habitats. Version July 2009. In: JNCC (Editor), Peterborough.

JNCC (2011) Towards an assessment of the state of UK peatlands. Joint Nature Conservation Committee report 445. http://jncc.defra.gov.uk/page-5861#download.

Johansen, M.P., Hakonson, T.E. and Breshears, D.D., 2001. Post-fire runoff and erosion from rainfall simulation: contrasting forests with shrublands and grasslands. Hydrological Processes, 15(15): 2953-2965.
Joys, A.C. and Crick, H.Q.P., 2004. Breeding periods for selected bird species in England: a report to JNCC. British Trust for Ornithology Research Report No. 352.
Kallis, G. and Butler, D., 2002. The EU water framework directive: measures and implications. Water Policy, 3: 125-142.
Kayll, A.J., 1966. Some Characteristics of Heath Fires in North-East Scotland. Journal of Applied Ecology, 3(1): 29-40.
Keeley, J.E., 2009. Fire intensity, fire severity and burn severity: a brief review and suggested usage. International Journal of Wildland Fire, 18(1): 116-126.
Kinako, P.D.S. and Gimingham, C.H., 1980. Heather Burning and Soil-Erosion on Upland Heaths in Scotland. Journal of Environmental Management, 10(3): 277-284.
Kuhry, P., 1994. The role of fire in the development of *Sphagnum*-dominated peatlands in western boreal Canada. Journal of Ecology, 82(4): 899-910.
Lance, A.N., 1983. Performance of Sheep on Unburned and Serially Burned Blanket Bog in Western Ireland. Journal of Applied Ecology, 20(3): 767-775.
Legg, C., Davies, G.M. and Gray, A., 2010. Comment on: 'Burning management and carbon sequestration of upland heather moorland in the UK'. Australian Journal of Soil Research, 48(1): 100-103.
Lehmann, J., Skjemstad, J., Sohi, S., Carter, J., Barson, M., Falloon, P., Coleman, K., Woodbury, P. and Krull, E., 2008. Australian climate-carbon cycle feedback reduced by soil black carbon. Nature Geoscience, 1(12): 832-835.
Lindsay, J., 2010. Peatbogs and Carbon: A critical synthesis RSPB Scotland.
Lindsay, R.A. and Ross, S., 1994. Monitoring of peat bog systems. Stapfia, 32: 73-92.
Lovat, L., 1911. The Grouse in Health and Disease: being the final report of the committee of inquiry on grouse disease. Smith, Elder & Co., London.
MacDonald, A.J., 2008. Fire and compaction as management tools on raised bogs. ROAME No. R07AC207, Scottish Natural Heritage Commissioned Report No. XXX.
MacDonald, A.J. and Haysom, K., 1997. Heather moorland management for lepidoptera. Information and advisory note, No. 58, Scottish Natural Heritage, Battleby.
Macdonald, A.J., Kirkpatrick, A.H., Hester, A.J. and Sydes, C., 1995. Regeneration by natural layering of heather (*Calluna vulgaris*): frequency and characteristics in upland Britain. Journal of Applied Ecology, 32(1): 85-99.
Mallik, A.U. and FitzPatrick, E.A., 1996. Thin section studies of Calluna heathland soils subject to prescribed burning. Soil Use and Management, 12: 143-149.
Mallik, A.U., Gimingham, C.H. and Rahman, A.A., 1984. Ecological Effects of Heather Burning .1. Water Infiltration, Moisture Retention and Porosity of Surface Soil. Journal of Ecology, 72(3): 767-776.
Mallik, A.U. and Rahman, A.A., 1985. Soil-water repellency in regularly burned Calluna heathlands - comparison of three measuring techniques. Journal of Environmental Management, 20(3): 207-218.
Mallon, D., Wheeler, P., Whiteley, D. and Yalden, D.W., 2003. Mountain hares in the Peak District. British Wildlife, 15(2): 110-116.
Maltby, E., 1980. The impact of severe fire on *Calluna* moorland in the North York moors. Bulletin d'Ecologie, 11(3): 683-708.
Maltby, E., Legg, C.J. and Proctor, M.C.F., 1990. The Ecology of Severe Moorland Fire on the North York Moors: Effects of the 1976 Fires, and Subsequent Surface and Vegetation Development. Journal of Ecology, 78(2): 490-518.
Maltby, T. and Edwards, T., 1984. Microbiological response to heather burning *in Moorland Management*, North York Moors National Park, Helmsley.

Marrs, R.H., 1986. The role of catastrophic death of Calluna in heathland dynamics Vegetatio, 66(2): 109-115.
Marrs, R.H., 1987. Studies on the conservation of lowland Calluna heaths. 2. Regeneration of Calluna, and its relation to bracken infestation. Journal of Applied Ecology, 24(1): 177-189.
Marrs, R.H., 1988. Vegetation change on lowland heaths and its relevance for conservation management Journal of Environmental Management, 26(2): 127-149.
Marrs, R.H., Phillips, J.D.P., Todd, P.A., Ghorbani, J. and Le Duc, M.G., 2004. Control of Molinia caerulea on upland moors. Journal of Applied Ecology, 41(2): 398-411.
McClymont, E.L., Mauquoy, D., Yeloff, D., Broekens, P., van Geel, B., Charman, D.J., Pancost, R.D., Chambers, F.M. and Evershed, R.P., 2008. The disappearance of Sphagnum imbricatum from Butterburn Flow, UK. The Holocene, 18(6): 991-1002.
McGilvray, J., 1995. An Economic Study of Grouse Moors. Game Conservancy, Fordingbridge.
McMorrow, J., Cavan, G., Walker, J., Aylen, J., Legg, C., Quinn, C., Hubacek, K., Thorp, S., M., T. and Jones, M., 2010. Fire Interdisciplinary Research on Ecosystem Services (FIRES) Policy Brief, pp. Available online at http://www.fires-seminars.org.uk/.
McMorrow, J., Lindley, S., Aylen, J., Cavan, G., Albertson, K. and Boys, D., 2009. Moorland wildfire risk, visitors and climate change. In: A. Bonn, T. Allott, K. Hubacek and J. Stewart (Editors), Drivers of Environmental Change in Uplands. Routledge, London and New York, pp. 404-431.
McMorrow, M.J.M., Cutler, M.E.J., Evans, M.G. and Al-Roichdi, A., 2004. Hyperspectral indices for characterizing upland peat composition. International Journal of Remote Sensing, 25: 313-325.
McVean, D.N. and Ratcliffe, D.A., 1962. Plant communities of the Scottish Highlands. Monographs of the Nature Conservancy No.1. HMSO, Edinburgh.
Meyles, E.W., 2002. Hillslope and watershed scale hydrologcial processes and grazing management in a Dartmoor catchment, Southwest England. PhD Thesis, University of Plymouth.
Miles, J., 1971. Burning Molinia-dominant vegetation for grazing by red deer. Grass and Forage Science, 26(4): 247-250.
Millennium Ecosystem Assessment, 2005. Millennium Ecosystem Assessment. Ecosystems and Human Well-being: Synthesis. Island Press, Washington, D.C.
Miller, G.R., Jenkins, D. and Watson, A., 1966. Heather Performance and Red Grouse Populations. I. Visual Estimates of Heather Performance. Journal of Applied Ecology, 3(2): 313-326.
Miller, G.R. and Miles, J., 1970. Regeneration of Heather (Calluna vulgaris (L.) Hull) at Different Ages and Seasons in North-East Scotland. Journal of Applied Ecology, 7(1): 51-60.
Mitchell, G. and McDonald, A.T., 1995. Catchment chracterisation as a tool for upland water quality management. Journal of Environmental Management, 44(1): 83-95.
Moss, D., Joys, A.C., Clark, J.A., Kirby, A., Smith, A., Baines, D. and Crick, H.Q.P., 2005. Timing of Breeding of Moorland Birds. British Trust for Ornithology Research Report No. 362.
Natural England, 2008. State of the Natural Environment Report 2008, Natural England, Sheffield.
Natural England, 2010a. England's peatlands: Carbon storage and greenhouse gases. Report Number NE257.
Natural England, 2010b. Managing for species: Integrating the needs of England's priority species into habitat management. Part 1 Report. Report Number NERR024.
NWCG, 2008. Glossary of wildland fire terminology. Available online at http://www.nwcg.gov/pms/pubs/glossary/pms205.pdf. Accessed 15th July 2010. National Wildfire Coordinating Group.

Okland, R.H., 1990. A phytoecological study of the mire Northern kisselbergmosen, SE Norway. 3: Diversity and habitat niche relationships. Nordic Journal of Botany, 10(2): 191-220.
PACEC, 2006. The economic and Environmental Impact of Sporting Shooting. A report prepared by Public and Corporate Economic Consultants (PACEC) on behalf of BASC, CA, and CLA and in association with GCT, Cambridge.
Page, C.N., 1997. The Ferns of Britain and Ireland. Cambridge University Press, Cambridge.
Peak District National Park Visitor Survey, 2005. Visitor survey - 2005, Peak District National Park Authority, Bakewell.
Pearce-Higgins, J.W., Grant, M.C., Beale, C.M., Buchanan, G.M. and Sim, I.M.W., 2009. International importance and drivers of change of upland bird populations. In: A. Bonn, T. Allott, K. Hubacek and J. Stewart (Editors), Drivers of Environmental Change in Uplands. Routledge, London and New York, pp. 209-227.
Peatscapes Project, 2008. Sphagna as management indicators research. Final report to North Pennines AONB Partnership.
Penny Anderson Associates, 2006. Analysis of recent moorland burning on the High Peak Estate, Derbyshire - 2006 Update. Report for the National Trust.
Picozzi, N., 1968. Grouse Bags in Relation to Management and Geology of Heather Moors. Journal of Applied Ecology, 5(2): 483-488.
Pietikäinen, J., Turunen, J. and Tolonen, K., 1999. The role of fire in the carbon dynamics of a mire, eastern Finland. Holocene, 9: 453-462.
Preston, C.D., Pearman, D.A. and Dines, T.D., 2002. The New Atlas of the British Flora. Oxford University Press, Oxford.
Preston, C.M. and Schmidt, M.W.I., 2006. Black (pyrogenic) carbon: a synthesis of current knowledge and uncertainties with special consideration of boreal regions. Biogeosciences, 3(4): 397-420.
Price, O., Russell-Smith, J. and Edwards, A., 2003. Fine-scale patchiness of different fire intensities in sandstone heath vegetation in northern Australia. International Journal of Wildland Fire, 12(2): 227-236.
Rackham, O., 1986. The History of the Countryside. Phoenix Press, London.
Ramchunder, S.J., Brown, L.E. and Holden, J., 2009. Environmental effects of drainage, drain-blocking and prescribed vegetation burning in UK upland peatlands. Progress in Physical Geography, 33(1): 49-79.
Ratcliffe, D.A., 2002. Lakeland. New Naturalist.
Rawes, M. and Hobbs, R., 1979. Management of Semi-Natural Blanket Bog in the Northern Pennines. Journal of Ecology, 67(3): 789-807.
Reed, M.S., Arblaster, K., Bullock, C., Burton, R.J.F., Davies, A.L., Holden, J., Hubacek, K., May, R., Mitchley, J., Morris, J., Nainggolan, D., Potter, C., Quinn, C.H., Swales, V. and Thorp, S., 2009a. Using scenarios to explore UK upland futures. Futures, 41(9): 619-630.
Reed, M.S., Bonn, A., Slee, W., Beharry-Borg, N., Birch, J., Brown, I., Burt, T.P., Chapman, D., Chapman, P.J., Clay, G.D., Cornell, S.J., Fraser, E.D.G., Glass, J.H., Holden, J., Hodgson, J.A., Hubacek, K., Irvine, B., Jin, N., Kirkby, M.J., Kunin, W.E., Moore, O., Moseley, D., Prell, C., Price, M.F., Quinn, C.H., Redpath, S., Reid, C., Stagl, S., Stringer, L.C., Termansen, M., Thorp, S., Towers, W. and Worrall, F., 2009b. The future of the uplands. Land Use Policy, 26(Supplement 1): S204-S216.
Robson, G., 1998. The breeding ecology of curlew Numenius arquata on North Pennine moorland. PhD Thesis, University of Sunderland, Sunderland.
Rodwell, J., 1991. British Plant Communities. Vol 2. Mires and Heaths. Cambridge University Press, Cambridge.
Rosenburgh, A. and Marrs, R., 2010. The Heather Beetle: a review. Report to the Heather Trust, available online at:

http://www.heathertrust.co.uk/assets/documents/144201011469_The_Heather_Beetle_-_a_review.pdf.

Scandrett, E. and Gimingham, C.H., 1989. Vegetative regeneration by layering in <i>Calluna Vulgaris</i> (L.) Hull. Botanical Journal of Scotland, 45(4): 323 - 333.

SEERAD, 2001. Prescribed fire on moorland. Supplement to the muirburn code: a guide to best practice. Scottish Executive Environment and Rural Affairs Department, Edinburgh.

SEERAD, 2008. The Muirburn Code. Scottish Executive Environment and Rural Affairs Department, Edinburgh.

Shaw, S.C., Wheeler, B.D., Kirby, P., Phillipson, P. and Edmunds, R., 1996. Literature review of the historical effects of burning and grazing of blanket bog and upland wet heath. English Nature Research Report No. 172.

Slack, N.G., 1990. Bryophytes and ecological niche theory. Botanical Journal of the Linnean Society, 104(1-3): 187-213.

Smith, A.A., Redpath, S.M., Campbell, S.T. and Thirgood, S.J., 2001. Meadow pipits, red grouse and the habitat characteristics of managed grouse moors. Journal of Applied Ecology, 38(2): 390-400.

Stewart, A., Pearman, D.A. and Preston, C.D., 1994. Scarce plants in Britain. JNCC, Peterborough.

Stewart, G.B., Coles, C.F. and Pullin, A.S., 2004a. Does Burning Degrade Blanket Bog? Systematic Review No.1 Centre for Evidence-Based Conservation.

Stewart, G.B., Coles, C.F. and Pullin, A.S., 2004b. Does burning of UK sub-montane, dry dwarf-shrub heath maintain vegetation diversity? Systematic Review No. 2, Centre for Evidence-Based Conservation.

Suckall, N., Fraser, E.D.G., Cooper, T. and Quinn, C., 2009. Visitor perceptions of rural landscapes: A case study in the Peak District National Park, England. Journal of Environmental Management, 90(2): 1195-1203.

Tallis, J.H., 1987. Fire and Flood at Holme Moss: Erosion Processes in an Upland Blanket Mire. Journal of Ecology, 75(4): 1099-1129.

Tallis, J.H., 1997. The pollen record of Empetrum nigrum in southern Pennine peats: implications for erosion and climate change. Journal of Ecology, 85(4): 455-465.

Tharme, A.P., Green, R.E., Baines, D., Bainbridge, I.P. and O'Brien, M., 2001. The effect of management for red grouse shooting on the population density of breeding birds on heather-dominated moorland. Journal of Applied Ecology, 38(2): 439-457.

Thompson, D.B.A., Gillings, S.D., Galbraith, C.A., Redpath, S. and Drewitt, A.L., 1997. The contribution of game management to biodiversity: a review of the importance of grouse moors for uplands birds. In: V. Fleming, A.C. Newton, J.A. Vickery and M.B. Usher (Editors), Biodiversity in Scotland: status trends and iniatives. Scottish Natural Heritage, Edinburgh, pp. 198-212.

Thurman, E.M., 1985. Organic Geochemistry of Natural Waters. Nijhoff/Junk, Dordrecht.

Tucker, G., 2003. Review of the Impacts of Heather and Grassland Burning in the Uplands on Soils, Hydrology and Biodiversity. English Nature.

Usher, M.B., 1992. Managment and diversity of arthropods in Calluna heathland Biodiversity and Conservation, 1(2): 63-79.

Van der Wal, R., Pearce, I., Brooker, R., Scott, D., Welch, D. and Woodin, S., 2003. Interplay between nitrogen deposition and grazing causes habitat degradation. Ecology Letters, 6: 41-146.

Vining, J. and Merrick, M.S., 2008. The influence of proximity to a national forest on emotions and fire-management decisions. Environmental Management, 41(2): 155-167.

Walker, J., Hewson, W. and McMorrow, J., 2009. Spatial pattern of wildfire distribution on the moorlands of the South Pennines., Moors for the Future Report to Pennine Prospects.

Ward, S.E., Bardgett, R.D., McNamara, N.P., Adamson, J.K. and Ostle, N.J., 2007. Long-term consequences of grazing and burning on northern peatland carbon dynamics. Ecosystems, 10(7): 1069-1083.
Welsh Assembly Government, 2008. The Heather and Grass Burning Code for Wales 2008.
Wheeler, B.D. and Proctor, M.C.F., 2000. Ecological gradients, subdivisions and terminology of north-west European mires. Journal of Ecology, 88(2): 187-203.
Whittingham, M.J., Percival, S.M. and Brown, A.F., 2000. Time budgets and foraging of breeding golden plover Pluvialis apricaria. Journal of Applied Ecology, 37(4): 632-646.
Whittingham, M.J., Percival, S.M. and Brown, A.F., 2001. Habitat selection by golden plover *Pluvialis apricaria* chicks. Basic and Applied Ecology, 2: 177-191.
Wigginton, M.J., 1999. British Red Data Books. 1. Vascular plants (3rd Edition). JNCC, Peterborough.
Willatt, S.T. and Pullar, D.M., 1984. Changes in Soil Physical-Properties under Grazed Pastures. Australian Journal of Soil Research, 22(3): 343-348.
Worrall, F. and Adamson, J., 2008. The effect of burning and sheep grazing on soil water composition in a blanket bog: evidence for soil structural changes? Hydrological Processes, 22: 2531-2541.
Worrall, F., Armstrong, A. and Adamson, J.K., 2007a. The effects of burning and sheep-grazing on water table depth and soil water quality in an upland peat. Journal of Hydrology, 339(1-2): 1-14.
Worrall, F., Armstrong, A. and Holden, J., 2007b. Short-term impact of peat drain-blocking on water colour, dissolved organic carbon concentration, and water table depth. Journal of Hydrology, 337(3-4): 315-325.
Worrall, F. and Bell, M., 2009. Best Practices for Managing Soil Organic Matter in Agriculture - Managing SOM in 'Upland' Agriculture. Final Report to Defra, Project SP08016.
Worrall, F., Bell, M.J. and Bhogal, A., 2010. Assessing the probability of carbon and greenhouse gas benefit from the management of peat soils. Science of the Total Environment, 408(13): 2657-2666.
Worrall, F., Evans, M.G., Bonn, A., Reed, M.S., Chapman, D. and Holden, J., 2009. Can carbon offsetting pay for upland ecological restoration? Science of the Total Environment, 408(1): 26-36.
Yallop, A., Thacker, J. and Clutterbuck, B., 2006a. Mapping extent of burn management in the North Pennines: Review of extent year 2001-2003. English Nature Research Reports No 698.
Yallop, A.R. and Clutterbuck, B., 2009. Land management as a factor controlling dissolved organic carbon release from upland peat soils 1: Spatial variation in DOC productivity. Science of the Total Environment, 407(12): 3803-3813.
Yallop, A.R., Clutterbuck, B. and Thacker, J., in press. Increases in humic dissolved organic carbon export from upland peat catchments: the role of temperature, declining sulphur deposition and changes in land management Climate Research.
Yallop, A.R., Thacker, J.I., Thomas, G., Stephens, M., Clutterbuck, B., Brewer, T. and Sannier, C.A.D., 2006b. The extent and intensity of management burning in the English uplands. Journal of Applied Ecology, 43(6): 1138-1148.
Yallop, A.R., Thomas, G., Thacker, J., Brewer, T. and Sannier, C., 2005. A history of burning as a management tool in the English uplands., English Nature Research Report No. 667. English Nature, Peterborough, UK.
Yallop, A.R., White, S.M. and Clutterbuck, B., 2008. Evidence for a mechanism driving recent observed trends in dissolved organic carbon release from upland peat soils. Apescts of Applied Biology, 85: 127-132, Shaping a Vision for the Uplands.