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MUIRBURN, PEATLAND AND PEAT SOILS – AN EVIDENCE ASSESSMENT OF IMPACT

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Summary

Fire has been integral to Scotland's uplands for millennia, both as a natural process and a land management tool. The latter, known as 'prescribed burning', is tightly regulated in Scotland ,as summarised in The Muirburn Code which was last revised in 2011 (http://www.gov.scot/Resource/Doc/355582/0120117.pdf). Scotland's Moorland Forum is in the process of reviewing the Code for the Scottish Government. ClimateXChange were asked to assess the current state of knowledge on the impact of muirburn on peatland and peat soils.

We found only limited new information to add to the small body of evidence relevant to Scotland, making it difficult to draw clear conclusions in some instances as evidence either conflicted or was missing for certain questions.

Key findings

- During burning there is a clear loss of vegetation (carbon). However this is replaced as the vegetation recovers during the burn cycle. What is not clear is whether there is a loss of carbon from peat soils.
- The evidence for a net loss of carbon dioxide is unclear. Following muirburn there tends to be an increase in loss of carbon dioxide through plant and soil respiration but also a gain through photosynthesis as the vegetation recovers. There is limited evidence for the loss of soil organic matter in regularly burnt areas but some evidence of accumulation of charcoal and other burnt residues. However, if muirburn is carried out incorrectly and ignites the peat, losses will be greater and little of the carbon is retained as charcoal.
- The timing of muirburn on peatland is critical, in that the vegetation should be dry enough for it to burn well while at the same time the ground should still be wet enough to prevent combustion of the ground litter and the peat itself.
- There is not enough evidence to judge the impact of vegetation type or age on greenhouse gas emissions. No studies have reported any real impacts on methane release and data on nitrous oxide is absent.
- The impact of muirburn on DOC (Dissolved Organic Carbon) losses has been subject to much debate; some studies have shown increases, some decreases and some no effect.
- The main factor affecting the rate of carbon sequestration post-muirburn is the nature of the recovering vegetation and whether it is grazed or not. Carbon sequestration post-muirburn will mainly be down to heather (or grass) re-growth in the short term. There is a consensus that Sphagnum mosses will aid it in the longer term; Sphagnum survives "cool" burns well and some experiments suggest that it benefits from rotational burning.

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Introduction

The practice of muirburn

Prescribed burning of moorlands has been used for centuries as a land management tool to remove less productive vegetation, mainly heather, and to encourage new growth. Originally used to increase productivity for sheep and cattle grazing, it is also now widely used to improve the habitat for red grouse. In Scotland, this is referred to as muirburn. The Muirburn Code sets out best practice for land managers carrying out muirburn (Scottish-Government 2011). The principal underlying legislation is the Hill Farming Act 1946, supplemented by various pieces of more recent legislation. Muirburn can be used to maintain the open aspect of moorlands (free of shrubs and trees), to create a mosaic of heather patches at different growth stages or to renew other vegetation such as grasses. Financial support for this activity can be made available in areas where muirburn could benefit Biodiversity Action Plan species such as skylarks and black grouse.

Peatland and peat soils

Many areas of moorland in Scotland are found on peat soils which may be defined as having an upper organic layer of at least 50 cm. Peatlands may be defined as areas having peat-forming vegetation. However, the two are not necessarily contiguous. Peat soils may, and often do, have a vegetation that is not peat-forming (or indeed no vegetation at all) while peat-forming vegetation may occasionally be found on shallower organic layers. This does have some practical implication as land owners will more readily see what may be peat-forming vegetation but have more difficulty in judging what lies beneath. The active layer in peat-forming soils is called the acrotelm (the upper layer within which the water table fluctuates) and the extent to which this is burned, particularly at the surface, will influence greenhouse gas (GHG) emissions.

The Muirburn Code and peatland

The Muirburn Code recommends that burning should not be carried out on blanket bogs and raised bogs on deep peat (>50 cm) unless heather constitutes more than 75% of the vegetation cover. Additionally, burning should not be carried out where there are peat haggs or other areas with exposed (unvegetated) peat.

The recommendations of the current Muirburn Code were based upon the best evidence, and judgement, available at that time (e.g. Towers et al. 2010). Despite this code of practice and the parallel codes for both England and Wales, the topic of prescribed burning of moorlands within the UK as a whole has remained a contentious issue with strong views on both sides of the argument, either promoting burning or calling for further restrictions. One outcome from this debate is a number of recent reviews that address the subject of burning on moorlands and peatlands (Cavan and McMorrow 2009, Worrall et al. 2010, Bain et al. 2011, Glaves et al. 2013, Lindsay et al. 2014, Davies et al. 2016b, Davies et al. 2016c). The issue has also led to much needed further research. One example is the results of the EMBER project, which focuses on impacts of burning on water quality (Brown et al. 2014). Since 2010 when the Muirburn Code was last reviewed, a search of the recent literature revealed over forty relevant research papers dealing with aspects of moorland burning within a UK context. Since a body of this work is from the north of England, it can be considered to be directly relevant to the Scottish situation, cognisant of the fact that there will remain north-south and east-west differences, even within Scotland itself. Hence it is now timely to take account of this new evidence base as part of reviewing the 2011 Muirburn Code.

Wildfires and Muirburn

In contrast to the controlled burning within a properly conducted muirburn (i.e. the fire is confined to a predetermined area), the peatland within moorland areas is also at risk from uncontrolled wildfires which are destructive to both vegetation and peat, may engulf nesting birds and other fauna, and may even spread to property and crops. Wildfires are most significant in upland regions where flammable fuels such as heather (*Calluna vulgaris*), gorse (*Ulex europaeus*) and purple moor grass (*Molinia caerulea*) dominate. The causes may be accidental, lightning strikes, arson or indeed muirburn which has gone out of control (i.e. areas not intended to be burnt are burnt or even those areas prescribed are burnt beyond the severity intended). It is usually prevalent in dry weather and in areas where there has been an accumulation of readily combustible plant material (fuel). Such fires will often burn hotter and can be more harmful than moorland properly managed by muirburn (Legg and Davies 2009) with potential loss of peat-forming vegetation, and this impacts both the quantity and the range of greenhouse gases emitted. One of the stated objectives of muirburn in some areas is to reduce the 'fuel load' and offset the danger and consequences of wildfire. This is particularly applicable to the rural-urban interface where there is both the increased risk of wildfire through population pressure and increased risk of damage to property. Muirburn may be used to provide firebreaks where wildfire risk is high at the urban interface or next to woodland. By the 2080s, summer mean temperature is projected to increase by just over 2.5 ºC in the north of Britain. It has been suggested that climate change will increase the risk of wildfire in areas where warmer and drier summers are predicted which will lower moisture levels, increasing the risk of ignition (Albertson et al. 2010).

Muirburn and the wider consequences for managing moorlands

Using muirburn needs to be considered in the context of how it affects the wider benefits that moorlands provide to a range of stakeholders. While a potential decrease in carbon sequestration and the emission of greenhouse gases may come immediately to mind when thinking about muirburn, we should equally recognise the important role of moorlands have in services such as food provisioning, water quality, flood mitigation, recreation, biodiversity, carbon sequestration and amenity. Not all stakeholders will value these in the same way. Hence, any cost-benefit analysis of muirburn will be heavily dependent upon the local context in terms of how this affects the value ascribed to each of these ecosystem services. Such values are not easy to apportion. Davies et al. (2016b) have pointed out that claims about the impacts of burning have not always been well substantiated and have raised the need for informed debate.

Muirburn, peatlands and greenhouse gas emissions

Greenhouse gases include carbon dioxide, methane and nitrous oxide. Burning vegetation leads to a proportion of the organic matter being converted to carbon dioxide (with minor amounts of methane and nitrous oxide). The amount of organic matter that turns into carbon dioxide and ends up in the atmosphere depends on how completely the material is combusted. Some of the vegetation can be partially burned and remains on the surface or is incorporated into the upper soil layers as charcoal (black carbon). The peat in peatlands is high in carbon and if the fire ignites the peat layer this will also produce carbon dioxide. It is important to distinguish the rapid loss of greenhouse gases during a burn and the subsequent effects of a burn on the exchange of greenhouses gases as the system recovers, i.e. net uptake of carbon dioxide through photosynthesis and loss of carbon dioxide through organic matter decomposition. Carbon is also lost from the system through leaching out of dissolved organic carbon or loss of particulate organic carbon into water courses where much of it is also slowly converted into carbon dioxide. Peat soils generally emit methane particularly when the peatland is in favourable condition. This is derived from lower layers, is closely linked with the water table height and hence is reduced by grips (drainage).

Climate warming is associated with wetter conditions in some areas and drier in others. This will have consequences for the water table. Thus the effect of muirburn and wildfires for GHGs needs to be considered in relation to the effects that a changing climate has on the carbon cycling.

Aim

Due to the sensitive and sometimes contentious views surrounding muirburn, we recognise that policy needs to be carefully founded on good evidence. Our aim is to provide the Scottish Government with an objective, up to date assessment of the available evidence relating to the impacts of muirburn on peatland and peat soils, particularly in relation to greenhouse gas emissions, and identify where evidence is simply lacking.

Search Methodology

In gathering evidence on the impact of muirburn and wildfire on peatland and peat soils we initially amased over 300 references from the literature. However, of these just over a 100 were relevant to the subject and only about 50 were judged as being useful to answering the set of specific questions posed. The majority were from studies in England, with very few coming from Scotland. Additionally, many were focused on one or other particular issue, rather than covering the breadth of questions.

We employed a standardised search methodology in order to gather the evidence to be assessed. The aim was do this in such a way as to be reproducible, comprehensive and without bias, with the evidence gathered from the peer-reviewed literature, reports, theses and other grey literature. Details are given in AnnexI.

Synthesis and Summary of the Evidence

1. What is the effect of muirburn on the release of greenhouse gases (GHGs)/carbon turnover?

Key Messages

- Following muirburn there tends to be an increase in loss of carbon dioxide through plant and soil respiration but also a gain through photosynthesis as the vegetation recovers, though this is not always detected.
- The evidence for a net loss of carbon dioxide is equivocal. There is limited evidence from three studies for the loss of soil organic matter in regularly burnt areas but this may be compensated to some extent by the accumulation of charcoal and other burnt residues. However, the evidence suggests that if the muirburn ignites the peat, losses will be greater and little of the carbon is retained as charcoal.
- Any loss of carbon through the erosion of bare peat declines as the vegetation re-establishes.
- No studies have reported any real impacts on methane release and data on nitrous oxide is absent. Most of these results come from work in the north of England with few studies being done in Scotland.

What we know

The site where the impacts of muirburn on greenhouse gases, and the carbon cycle in general, have been most studied is the Hard Hill experiment at Moor House in the North Pennines. This is a fully factorial and replicated (four blocks) experiment on blanket bog with burning and grazing as treatments, with the burning on both a 10-year and 20-year cycle plus control (unburned) plots, set up in 1954 (See Fig.1 in Ward et al. 2012). Whilst being in England, the altitude and exposure of this site make it representative of many upland blanket bog sites in Scotland. Susan Ward completed her Ph.D. at this site and included measurements of carbon dioxide and methane on the 10-year and unburnt plots (Ward 2006). Both total respiration and photosynthesis were significantly increased compared to the unburnt control and the net carbon dioxide flux showed uptake, which was also significantly greater in the burnt plots (Ward et al. 2007). However, this cannot be taken as an overall increase in sequestration as fluxes were only determined over two hours at midday. Clay et al. (2010), using spot measurements but applying an extrapolation methodology, similarly showed significantly increased primary productivity on the burnt plots; total respiration values were similar for both burn and no burn, resulting in net carbon dioxide flux showing a loss but much reduced in the burnt plots. Savage (2011) also examined this site and found it to be a net carbon dioxide source but found no differences between treatments; unfortunately her results were pseudoreplicated on one block, raising doubts about her findings. Ward et al. (2012) did a follow-up experiment using a ^{13}C-carbon dioxide pulse chase technique. They showed increased photosynthetic uptake and subsequent transfer to the soil microbial biomass in the burned plots but no impact of burning on NEE (net ecosystem exchange).

At a site in the Yorkshire Dales, Farage et al. (2009) found no difference in soil respiration between recently burned, 12- 15 year old heather and unburned sites, though measurement was only made on one occasion. In contrast, and taking heather canopy height as a proxy for time since burning, Dixon et al. (2015) studying three sites in the South Pennines and Peak District showed that ecosystem respiration was positively correlated, and photosynthesis negatively correlated, to time since burning. There was no canopy height at which the system was a C sink and NEE increased positively with canopy height. At three sites in Scotland (two muirburn and one wildfire) there was no difference detected in ecosystem respiration between burned and unburned sites (Taylor 2015).

Few studies have looked at impacts of burning on methane fluxes. Ward et al. (2007) found that burning reduced methane fluxes slightly but were unable to explain why. However, both Ward et al. (2012) and Taylor (2015) found no effect of burning on methane emissions. Clay et al. (2010) reported significant effects of burning on methane emissions but emissions were not actually measured but predicted from water table depth. Clay et al. (2015) later reported no significant trend of methane across a burning chronosequence but again values were based on water table depth. (Though these authors note their use of a proxy to estimate methane, it is a bit misleading to report any impacts on methane when they are really impacts on water table.) Worrall et al. (2011) measured relatively low methane fluxes at a wildfire site but found no significant difference between the burnt site and adjacent unburnt areas; only one of two restored areas showed significantly higher methane.

Besides measuring carbon dioxide and methane fluxes, carbon turnover in peatlands can be gauged by looking at the change in carbon stocks. Measuring small changes in organic matter in a largely organic and spatially variable landscape is challenging (Chapman et al. 2013). Imeson (1971) measured surface erosion losses from recently burnt heather on the North York Moors and found that the rate of erosion correlated negatively with the height and density of vegetation but concluded that any losses were small once complete canopy cover had been obtained. It wasn't clear from his study whether the burns examined were wildfire or controlled burns. Kinako and Gimingham (1980) used marker pins inserted into the peat to follow surface erosion losses in the two years following controlled burning in the North East of Scotland. Again they concluded that erosion ceased once vegetative cover was reestablished.

Garnett et al. (2000), using the Hard Hill plots, measured the carbon stocks located above a time marker in the organic profile. The marker was the occurrence of a defined level of spheroidal carbonaceous particles, which originate from the onset of observable impact of global industrialisation (fossil fuel burning) in the area, estimated to have taken off in the period 1940-1950. While carbon stocks to this level were unaffected by grazing, the 10-year cycle of burning had brought about a significant reduction (23 t C ha^{-1} over 32 years), comparing the burnt and grazed treatment with the grazed and unburnt treatment. Unfortunately, for some reason the burnt and ungrazed treatment was not included, although it could be argued that the presence of light grazing is closer to the real life situation. Ward et al. (2007) also measured carbon stocks on the Hard Hill plots. They found no significant difference in total carbon stock but were unlikely to do so since they sampled to 1 m rather than to a fixed datum (Chapman et al. 2013). However, they reported a significant reduction (almost 60%) in the carbon in the combined F and H (decomposing litter) horizons.

Besides the gain or loss of soil organic matter there is the potential for gains in charcoal (generally coarser material) or black carbon (usually smaller soot-like particles) formed during partial combustion in a burn. Stevenson et al. (1996), examining a range of Scottish moorlands, showed a clear link between the incidence of controlled burns and the accumulation of larger sized charcoal particles in the soil surface horizons (see also Rhodes 1996). While they sized and counted the charcoal particles, they did not estimate the charcoal mass. In contrast, Grand-Clement (2008), using both Moor House and Peak district sites, found no impact of burning on black carbon levels. These were estimated as accounting for 3 – 8% of soil carbon depending on the soil horizon examined and it was concluded that much had originated from fossil fuel burning rather than from heather burning. Black carbon is not synonymous with charcoal but overlaps with it and quantification is very dependent upon the methodology used. Clay and Worrall (2011) found 4.3% of the biomass consumed during a burn ended up as black carbon and concluded that this could be an important carbon sequestration mechanism, although this was in the context of a wildfire rather than a controlled burn. A subsequent study of controlled burns put the contribution to "char" carbon rather less at 2.6% (Worrall et al. 2013a). Paradoxically, these authors suggested that fast burns and high temperatures could increase long-term carbon sequestration through the production of char. It is perhaps worth noting that this only applies to the combustion of above-ground biomass; where peat itself is burned very little is converted to charcoal (Hudspith et al. 2014).

Areas of active research and debate

A legitimate question is the extent to which the Hard Hill experimental plots at Moor House are representative of blanket bog across the country since the relevant experimental research is heavily weighted towards this site. The rather slow and poor growth of *Calluna* following muirburn at this site (e.g. Santana et al. 2016) would suggest that Moor House is perhaps more at one extreme of the climate envelope. With regard to sequestration in charcoal, Santin et al. (2016) argue that very little pyrogenic C (a term which includes black carbon and charcoal) is formed during prescribed burns but increases in wildfire. However, they describe vegetation fires in general and it is unclear to what extent this applies to peat fires, particularly given the comments by Hudspith et al. (2014).

The findings by Farage et al. (2009) which suggest little effect of burning on the carbon cycle have been questioned by Legg et al. (2010). They indicate that the losses of above-ground biomass calculated by Farage et al. were unrealistically low and that to conclude that there was no impact of burning on carbon losses was misleading. Farage et al. (2010) acknowleged the limitations of their study and effectively suggest that their losses of above-ground biomass may have been particularly low.

What we don't know

There have been no studies looking at the impact of burning on nitrous oxide emissions. Nitrous oxide emissions from nutrient-poor peatlands are generally very low to negligible (Thomson et al. 2012, Sozanska-Stanton et al. 2016, Tomlinson et al. 2016) so impacts are also likely to be low. Farage et al. (2009) estimated the nitrous oxide emissions during the actual burning of above-ground biomass using IPCC default values but in situ emissions during heather burning are unknown.

a) Is there evidence that the release of GHGs/carbon turnover is affected by timing of muirburn (linked to moisture levels in vegetation and soils)?

Key messages

- There is a considerable body of evidence relating to the ignition and spread of fire, much of it in the context of wildfire and beyond the scope of this assessment.
- However, it is clear that moisture levels play a key role: moisture in the heather needs to be <60% for a good burn but moisture in the litter and peat needs to be >100% to avoid these layers being lost.
- How GHG emissions post-burn vary with different soil and vegetation moisture levels is unknown.

What we know

Peat itself is more likely to ignite when the moisture content (mass of water per dry mass of peat) is <93% (Benscoter et al. 2011) — 95% (Hartford 1989) while *Sphagnum* moss may still ignite around 120% (Frandsen 1997). Grau et al. (2015) have recently suggested these limits could be 125 and 100%, respectively, while Prat-Guitart et al (2016) give a critical moisture content of 115% for peat with a bulk density of 0.15 g cm^{-3} and 150% for peat at 0.075 g cm^{-3}, though these were based on laboratory tests. In summary, where muirburn is conducted over peats with a moisture content <100%, there is a danger of the peat itself igniting and continuing to smoulder, leading to increased carbon loss (Davies et al.
2013, Grau et al. 2015).

Moisture levels in the above ground biomass are also critical. Generally, the content of live heather needs to be <60% for ignition (Legg and Davies 2009) and the actual moisture content will influence the rate of spread of the fire (Davies and Legg 2008). Additionally, the proportion of dead to live material is important, particularly as their moisture contents can differ and change with the season (Davies 2005).

Davies et al. (2016a) showed how fuel consumption during wildfires increased as fuel moisture levels decreased. Carbon released was 3.6 —10 t C ha^{-1} of which about half was due to the consumption of ground material (litter, moss, decayed vegetation). In contrast, the prescribed burns they reported on lost very little of their ground material though these were experimental and may not reflect muirburn in practice (see Legg et al. 2007).

Areas of active research and debate

The prediction of incidence and severity of wildfire has been, and continues to be, of concern. Better understanding the factors that influence ignition of the vegetation, ground materials and the peat is called for in order to develop tools to help predict when wildfire risk is high. What is unclear is the extent to which findings can be extended to prescribed burns (Davies et al. 2016a).

What we don't know

While the timing of muirburn, which will influence moisture levels in live and dead above-ground material, and in the ground material and peat, clearly will impact on the extent and severity of fire and associated carbon losses, the effect on any subsequent GHG losses are unknown. The exception would be where the fire has ignited the peat layer leading to carbon losses through burning and subsequent carbon losses through erosion until the area becomes re-vegetated. This generally applies more to a wildfire than to a prescribed muirburn situation. There is a gap in understanding how the system's underlying moisture interacts with weather indices to influence the risk for wildfire, i.e. the link between fuel structure, weather, fire intensity, burn severity and post-fire ecosystem responses (Davies et al. 2013).

b) Is there evidence that the release of GHGs/carbon turnover is affected by frequency of muirburn?

Key message

- This is an area where there has been little study and experimental evidence for the effect of burn frequency on the carbon cycle is limited and inconclusive; the evidence that has been identified is mainly based on modelling.
- This suggests for Scotland that carbon in the above-ground vegetation is optimized by longer (20-50 year) muirburn cycles but that there is an interaction with the frequency of wildfire. It is difficult to draw any definitive conclusions for impacts on the below-ground carbon.

What we know

Experimental evidence is largely limited to the Hard Hill plots which include both 10-year and 20-year cycles, but most studies have focused on just the 10-year cycle plots. Grand-Clement (2008) did compare both for black carbon but found no differences between the 10-year, 20-year and zero burn sites. Clay et al. (2010) also compared both; they showed that the 20-year plots were intermediate between the 10-year and no burn plots in terms of overall budget but it was unclear if there was a statistically significant difference between these two cycles. Combining annual losses with projected burn losses in a modelling exercise, they concluded that both 10- and 20- year cycles would result in cumulative losses greater than in the no burn scenario but with the cycle extended to 25 years there would be a break- even point. However, if the combustion rate was reduced from 85% to 61% (i.e. a much reduced fire intensity); the break-even point was reduced to 15 years.

A few studies have looked at frequency of muirburn impacts but only on the above-ground biomass. Allen et al. (2013) modelled fuel load at a site in the Peak District and looked at the interaction between frequency of muirburn and wildfire return interval. For a scenario based on a 50-year wildfire interval, 8-year prescribed burning cycles minimized the biomass carbon loss whereas a 200-year wildfire return interval required long muirburn cycles (50 years or more). Alday et al. (2015), using the Hard Hill plots, found that biomass on the no-burn (since 1954) plots was the same as that on the reference no-burn (since ca. 1924) plots. *Calluna* biomass in the less frequently burned (20-year cycle) plots would reach this level asymptotically after 20 years but the more frequently burned (10-year cycle) plots would clearly never reach this. They concluded that a 20-year burning cycle would maximize carbon fixation. Santana et al. (2016) extended the concepts of Allen et al. (2013) and Alday et al. (2015) to several sites across the UK including one in Scotland (Kerloch, North East Scotland). The optimal muirburn frequency for maximizing carbon varied, with the more northern sites (Kerloch and Moor House; colder and wetter) needing 30 — 50 years and the more southern sites (Howden and Dorset; warmer and drier) needing either 8 —10 years or 30 — 50 years with intermediate rotation lengths giving greater carbon loss. This would suggest the optimum for most Scottish sites is 30 – 50 years. Decreasing the wildfire return frequencies only served to increase carbon loss at the northern sites without changing the optimal muirburn frequency. However, for the southern sites, decreasing the wildfire return frequency to 50 years made the shorter (8 — 10 year) muirburn rotation more favourable for reducing carbon loss.

Areas of active research and debate

Clearly the range of findings on the frequency of muirburn for optimal carbon sequestration is varied, even confusing, and is hampered by the lack of on the ground studies.

What we don't know

The modelling studies give some indication of above-ground biomass changes, but we have no information on what may be happening to litter and below-ground carbon pools or how other losses to DOC, etc., may be affected by the burning interval.

c) Is there evidence that the release of GHGs/carbon turnover is affected by type of fire (muirburn v wildfire) and if so, is the reason for the difference clear (e.g. vegetation moisture content, time of year, etc.)?

Key message

- There is clear evidence that, on average, much more carbon dioxide is released during wildfire than during muirburn due to the fact that wildfire can occur at any time, when both the vegetation and peat are dry and/or when other conditions (e.g. wind speed, wind direction, temperature, fuel load) promote a severe burn.

What we know

In general, we would expect the release of carbon during a burn to be greater in the case of wildfire compared to muirburn as the former are usually much more intense, leading to losses of not only all the vegetation but also the litter and sometimes surface peat layers. Hence Davies et al. (2016a) clearly showed similar above ground biomass consumption between wildfire and muirburn (2–12 t ha^{-1}) but significant additional ground fuel consumption during wildfire (another 3-10 t ha^{-1}). Hudspith et al. (2014) describe a range of wild fire severity on a raised bog which varies from light (shrub layer foliage and twigs consumed; stems scorched/partially charred, similar therefore to a "cool" controlled burn), through moderate (stems also consumed; charred bryophytes and surface peat), to deeply burned (all shrub and bryophytes consumed/charred; peat charred and roots exposed). The situation where wildfire has removed all vegetation and the peat has remained bare is not uncommon (Maltby et al. 1990, Mackay and Tallis 1996, Gilbert 2008). At the other end of the scale, Taylor (2015) describes the wildfire at Forsinard as only consuming the canopy and patches of Sphagnum, not too different from a "hot" controlled burn.

Other effects of a moderate to severe wildfire or of a "hot" controlled burn is making the peat surface hydrophobic (Maltby et al. 1990) and killing the seed bank (Legg et al. 1992) leading to, respectively, increased water run-off and difficulties in re-establishing vegetation.

What distinguishes muirburn from wildfire is that muirburn is restricted to certain time periods when, the ground material is likely to be wet (>100% moisture) whereas wildfire can occur at any time and in fact is more likely when conditions are dry.

Areas of active research and debate

Where prescribed fire turns into wildfire it would imply that, unless the prescribed burning is being done out of season, the timing would be the same as for muirburn and, possibly, such burns, although more destructive than muirburn, may be less likely to consume appreciable ground material and/or peat. However, this is conjecture and requires more research comparing in season and out of season wildfires.

What we don't know

There is very little information on how carbon losses, apart from erosion losses, compare following either wildfire or muirburn, e.g. losses via respiration, methane or DOC.

d) Is there evidence that the release of GHGs/carbon turnover is affected by vegetation type or age (e.g. heather versus grass, age/physiological state of heather)?

Key message

- There is not enough evidence to be able to answer this question. Most studies are concerned with heather-dominated communities. It is known that repeated fire can favour *Molinia* encroachment and lead to dominance (Hamilton 2000, Brys et al. 2005) but it not known how this might impact GHG emissions following a burn.

e) What are the relative proportions of carbon lost to the atmosphere at the time of burning, through DOC (Dissolved Organic Carbon), POC (Particulate Organic Carbon) and from soil erosion (under different conditions as above)?

Key message

- The impact of muirburn on DOC losses (soluble organic compounds from decayed vegetation that may be lost in streams and rivers) has been subject to considerable debate; some studies have shown increases, some decreases and some no effect. Where there are increases, they may be very temporary following a burn. We do not understand all the processes involved.
- There is limited evidence that there will be small losses of POC (finely divided organic material carried in water courses) from burned catchments which represent a transfer of carbon from the burn site, possibly to a deposition site elsewhere.

What we know

The topic of carbon losses through leaching and drainage from burnt catchments has been well-studied due to its importance in impacting water quality and the cost of removal from drinking water supplies. At the same it has proved to be one of the most controversial over the past decade. In an early study, Martin (1992) highlighted this problem in the North York Moors and showed how a severe burn led to increased colour. However, Worrall et al. (2007) found that DOC in soil solution actually decreased with burning on the Hard Hill plots, Savage (2011) found the same and Ward et al. (2007) reported no effect of burning at this site. Subsequent studies at the same site also suggested no effect of burning on DOC in soil pore water and run-off water except in the first few weeks following a burn (Clay et al. 2009, Clay et al. 2010). Similarly, Chapman et al. (2010) found no impact of burning on DOC in stream water samples from the River Nidd catchment, North Pennines. Recently, Evans et al. (2016) reported a reduction in DOC concentrations at a wildfire impacted moorland site in Northern Ireland. In contrast, studies on catchments in the South Pennines and North York Moors consistently showed increases in drainage DOC concentration correlated with the increasing area of recent peat burns (Clutterbuck 2009, Yallop and Clutterbuck 2009, Clutterbuck and Yallop 2010, Yallop et al. 2010). Worrall et al. (2011), mainly studying restoration from wildfire reported greatest DOC losses from a comparative managed burn site. This was estimated at 0.96 t C ha^{-1} yr^{-1} compared with the non-burnt control site at 0.13 t C ha^{-1} yr^{-1}. Literature values are usually in the range of 0.04 — 0.29 t C ha^{-1} yr^{-1} (Yallop et al. 2010).

Fewer studies have looked at POC. Rhodes (1996) reported how moorland burning resulted in charcoal deposits in lake sediments, indicating how carbon can move from one location to another as a consequence of burning. Worrall et al. (2011) also estimated POC losses in their restoration study; they recorded 0.38 t C ha^{-1} yr^{-1} from the managed burn site, compared to 0.03 t C ha-1 yr-1 from the control site and 15.5 — 20.1 t C ha-1 yr-1 from their bare eroding sites that had suffered from severe wildfire. Ramchunder et al. (2013) found that burned catchments were higher in POC levels and that these correlated with impacts on benthic invertebrates while Evans et al. (2016) reported increased POC losses of
1.5 t C ha^{-1} yr^{-1} from their wildfire impacted site.

Areas of active research and debate

There is much debate in the literature over the extent that burning leads to elevated DOC levels. Yallop et al. (2012) have disputed the findings and methodology of Chapman et al. (2010) who detected no change in water colour due to burning but Chapman et al. (2012) have made a detailed rebuttal of their criticism and hold that burning is not a major factor in DOC loss from peated catchments. There is a plea for much more research at both the plot and catchment scale to resolve this. Clay et al. (2012) also make the point that colour and DOC are not always equivalent; in their study in the North Pennines colour increased in the few years following burning but DOC was not changed.

What we don't know

We still do not know if prescribed burning of peatland results in appreciable DOC release or whether other factors, such as recovery from acid rain, can explain these conflicting observations. Studies to date are nearly all from England making the situation for Scotland even more unclear, particularly as these English sites are subject to much greater pollution levels (nitrogen, sulphur, heavy metals) than those north of the border. The only Scottish study we are aware of is that of Helliwell et al. (2010) where experimental burning reduced DOC levels; however, this was on an alpine heath rather than blanket peat.

2. What factors affect carbon sequestration rates post-muirburn, e.g. pre- and post-fire vegetation (including specific impacts on species such as Sphagnum), grazing, length of burn rotation, age of heather, burn intensity?

Key message

- Carbon sequestration post-muirburn will mainly be down to heather growth in the short term.
- There is a consensus that *Sphagnum* mosses are beneficial in the longer term but the best length of burn rotation is unclear.
- Grazing, particularly over-grazing, will decrease recovery but the interaction between grazing pressure, burn interval and fire intensity on *Sphagnum* recovery or regeneration is not well understood.

What we know

A complete answer to this is not really available from the current literature. The main driver for carbon sequestration post-burn is the reestablishment and growth of above-ground vegetation, in most cases this is predominantly *Calluna* but understorey mosses such as *Sphagnum* and other vascular species will contribute. Subsequently litter will also accumulate. The growth curves of Santana et al. (2016) show the overriding influence of location (soil type and fertility) and climate (temperature and precipitation). Growth at Moor House is slowest and asymptotes to a relatively low mass for both *Calluna* and litter while the projections for Dorset and Kerloch (North East Scotland) are more than double those at Moor House. Growth at Howden (South Pennines) was even greater and was still increasing after 50 years.

There is some evidence that the water table can be higher following burning as the reduced vegetation has reduced water demand through evapotranspiration (Worrall et al. 2007). This will initially aid carbon sequestration as peatlands can act as a sink when the mean water table is within 6.5 cm of the surface, transitioning to an increasing net carbon dioxide source as water table drops below this threshold (Couwenberg et al. 2011). Hence, Dixon et al. (2015) found that blanket bog with well-developed *Calluna* vegetation was a net carbon dioxide emitter because soil respiration, enhanced by the low water table, was greater than photosynthesis.

There is a consensus that the presence of *Sphagnum* will promote carbon sequestration since these species have historically contributed to peat accumulation (Blundell and Holden 2015). Hence management should be aimed towards increasing *Sphagnum* presence (Savage 2011). Lee et al. (2013a) found that it was the 10-year burn cycle rather than the 20-year cycle that promoted greater *Sphagnum* and *Eriophorum* presence but confusingly Lee et al. (2013b) found that at another site longer term rotations promoted *Sphagnum* return. This requires more study. Interestingly, the presence of *Sphagnum* moss may limit the loss of carbon during a burn (Shetler et al. 2008). The extent to which *Calluna* replaces *Sphagnum* or *Sphagnum* can be regenerated post-burning is of importance here but there are few studies that have provided experimental evidence.

It is fairly well established that over-grazing following burning will severely hamper revegetation (e.g. Mackay and Tallis 1996) but that very sparse grazing such as seen at Moor House (0.04 sheep ha^{-1} in summer) has only a slight effect (22% reduction in biomass C: Ward et al. 2007). Similarly, a severe burn that removes most vegetation cover will prevent vegetative carbon sequestration possibly for decades. However, it is unclear to what extent “cool” burns and “hot” burns, in the context of a controlled burn, will impact overall carbon sequestration.

What we don’t know

As intimated above, much is still unclear. Any study should account for all facets of the carbon cycle, not just vegetation but including DOC and POC losses, changes to litter and peat carbon, methane emissions and accumulation of charcoal. As far as we are aware, only Worrall and colleagues have attempted a complete carbon budget for peatlands in England (Worrall et al. 2009, Clay et al. 2010, Worrall et al. 2011); there is potential for such an approach covering sites in Scotland.

3. How is peat-forming vegetation affected by muirburn (under different conditions as above)?

Key message

- The effects of muirburn on the peat-forming species *Sphagnum* are not fully understood with variable impacts recorded. It is known that *Sphagnum* can survive "cool" burns well and may protect the underlying peat but will succumb to a "hot" burn that penetrates too far into the moss layer.

What we know

From studies in North-West Scotland, Hamilton (2000) found that *Sphagnum* was damaged by a single fire event but could recover after two years, providing it wasn't poached too much. Using the Hard Hill experimental plots, Lee et al. (2013a) found that heather (*Calluna vulgaris*) and moss (*Hypnum jutlandicum*) increased over time on the reference no- burn plots (outwith the main experimental plots, last burned ca. 1924). On the main no-burn plot (last burned 1954) and the 20-year cycle plots heather also increased but on the 10-year cycle plots the peat-forming species *Eriophorum* and *Sphagnum* increased. If water tables post burning are raised (see above) then this might promote *Sphagnum* growth.

More light and space might promote *Sphagnum* and there are suggestions of burnt *Calluna* stems providing a 'climbing frame' for Sphagnum development (Hamilton 2000). However, these mechanisms requires verification. In laboratory studies, Taylor (2015) showed how *Sphagnum* showed considerable resilience to burning treatments but that long-term recovery was likely to be better for spring burns than for autumn burns.

4. What is the difference in the effect of muirburn on GHG emissions compared to other management actions designed to influence peatland vegetation regrowth (cutting, etc.)?

Key message

- As an alternative to muirburn, heather growth can be cut and either physically removed or left in place. However, there have been insufficient studies on cutting to gauge the effects on GHG emissions.

What we know

The only study we are of aware of where cutting was employed is that in the Goyt Valley in the Peak District (Worrall et al. 2013b, Qassim 2015). Here they found that both burning and cutting significantly reduced DOC concentrations in soil and run-off water but there was no difference between burning and cutting.

What we don't know

There is clearly scope for further studies on cutting, both on DOC but particularly on GHG emissions.

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Annex I. Search Methodology

Scope of the work:

- Geographical reference: Principally Scotland but including the whole of the UK and Ireland. It was agreed that studies from similar oceanic temperate areas to UK peatlands, based upon the Koeppen-Geiger climate zones, would also be investigated.
- Language restrictions: English language literature only.
- Date restrictions: mainly up until September 2016. The majority of the peer-reviewed literature was done 5-20 September, some grey literature was done up to 22 October and Dart–Europe E-theses done on 17 November.
- Population restrictions: Peat soils and peatlands, principally blanket bog, with a surfice organic layer > 40 or 50 cm. May include results from areas with blanket bog vegetation with a surface organic layer < 40 or 50 cm if relevant or depth not specified. Studies on wet heath were also assessed for relevance to peat and peatland areas.

Framing the review questions:

1. What is the effect of muirburn on the release of greenhouse gases (GHGs)?

- Is there evidence that the release of GHGs/carbon turnover is affected by timing of muirburn (linked to moisture levels in vegetation and soils)?
- Is there evidence that the release of GHGs/carbon turnover is affected by frequency of muirburn?
- Is there evidence that the release of GHGs/carbon turnover is affected by type of fire (muirburn v wildfire) and if so, is the reason for the difference clear (e.g. vegetation moisture content, time of year, etc.)?
- Is there evidence that the release of GHGs/carbon turnover is affected by vegetation type or age (e.g. heather versus grass, age/physiological state of heather)?
- What are the relative proportions of carbon lost to the atmosphere at the time of burning, through DOC (Dissolved Organic Carbon), POC (Particulate Organic Carbon) and from soil erosion (under different conditions as above)?

2. What factors affect carbon sequestration rates post-muirburn, e.g. pre- and post-fire vegetation (including specific impacts on species such as Sphagnum), grazing, length of burn rotation, age of heather, burn intensity?

3. How is peat-forming vegetation affected by muirburn (under different conditions as above)?

4. What is the difference in the effect of muirburn on GHG emissions compared to other management actions designed to influence peatland vegetation regrowth (cutting, etc.)?

Searching and locating the evidence

Search Terms:

(burn* OR *fire OR muirburn OR swaling)

AND (bog OR heath OR moor* OR peat* OR mire)

AND (carbon OR DOC OR POC OR GHG OR greenhouse gas*)

AND (UK OR United Kingdom OR England OR Scotland OR Wales OR Ireland OR Brit*)

The last term was also substituted using Iceland, Norway, Sweden, France, Belgium, Netherlands, Germany, Denmark, Switzerland, Austria, Czech Republic, Poland, Slovakia Hungary, Croatia, Serbia and British Columbia.

Search ‘locations’:

Web of Science, Google Scholar, Scopus

‘Grey literature’ searches were performed on websites belonging to SNH, NE, FC, JNCC and their Irish equivalents. Steering group members were also approached for any additional material that they were aware of. Thesis searching was done using British Library EThOS and DART-Europe E-theses.

Assessing and collating the evidence

All references were downloaded into EndNote X7. However, bulk downloading of references from Google Scholar does not run smoothly and results in corruption of much of the information. Hence we used Zotero (version 4.0.29.10 http://zotero.org) as an intermediary. Zotero was efficient in obtaining information, including pdfs or HTML pages where available, and had the facility to export references into EndNote. (We did not need to use “downthemall” or “import.io” as had been originally suggested.) Missing pdfs were obtained using EndNote’s “Find Full Text” facility but some full texts had to be obtained as hard copy through the Institute’s inter-library loan.

The identified literature was sifted in two stages:

1. Title/Abstract screening. Two of the review team independently reviewed the titles and abstracts and classified them as either not relevant or possibly/definitely relevant. Where there were differences in classification, these were reassessed by one reviewer and the new classification conformed by the other reviewer. The aim was to screen out obviously irrelevant studies, e.g. those referring to ‘burns’ as in streams or to ‘muirburn’ merely in passing as one of many factors impacting peatlands.
2. Full text screening. All papers identified in 1 above as possibly/definitely relevant were read in full and summary information entered into an Excel spreadsheet with columns for each category of specific information required about paper relevance and content. On the basis of this full reading, papers were further screened as either “relevant/definitely useful/essential to assessment” or “not contributing to answering the questions”.

Column headings in Excel spreadsheet included:

- Endnote Reference Number
- Reviewer
- Paper details
- PDF available (Y/N)
- Country
- Site
- Muirburn or wildfire or both (M/W/B)
- Effect on GHG/carbon: direct or indirect (YD/YI/N)
- Review (Y/N)
- Original data (Y/N)
- Year(s) of data collection
- Peatland or peat soil (Y/N/U)
- Vegetation type: bog [raised/blanket], wet heath, grassland, other (BB/BR/WH/G/O)
- Time since last burned in years (#/N)

- Muirburn aimed at management for grouse, grazing, other, none specified (GR/GZ/O/NA)
- Data from before/after muirburn; correlative / qualitative data (BC/AC/BQ/AQ)
- Comparative data from unburned area (Y/N)
- Time series data (Y/N)
- Data on burning interval or repeat burning (Y/N)
- Data on impact of muirburn on peat forming vegetation (Y/N)
- Data on carbon losses to soil (leaching) (Y/N)
- Data on carbon losses (DOC, POC) in water courses (Y/N)
- Data on carbon accumulation as charcoal (Y/N.)
- Data on GHG emissions as carbon dioxide, methane, nitrous oxide (C/M/N)
- Comments

Documents (reference lists, Excel spreadsheets, etc.) are lodged on Engage for easy access by the steering group.

Assessing the quality of the evidence

The quality of evidence within each study was assessed using agreed criteria and scored as to whether it was relevant or not relevant to answering the questions posed.

Synthesising and summarising the evidence

Once each study/paper/report was characterised in relation to its relevance, scope and quality, the relevant evidence that it contains was extracted and put into the context of the specific questions that frame this assessment. The form that this takes was discussed and agreed with the steering group.

Search Results

Table 1 shows the number of references obtained from the various databases. We initially sourced 106 from Web of Science; 87 were from UK and Ireland and a further 19 from similar Koppen-Geiger climate areas. The numbers from the other databases are additional, after removing duplicates. Scopus added very few. Google Scholar added a large number though subsequent screening found many of these were not relevant. Part of the problem was that the Google Scholar search facility is much more limited than that available within Web of Science. During the full text screening it was clear that some very pertinent references had not been captured and so these were subsequently added in.

Table 1. Numbers of references obtained from database sources in initial screening

Database	Number of references
Web of Science	106
Scopus	6
Google Scholar	151
EThOS	15

Grey literature	4
Dart-Europe E-theses	4
Other references cited in “relevant” papers	20
Total	306

The initial title/abstract screening removed 196 references, leaving 110 to be further screened for full text relevance. Out of these 110, 53 were considered to be “relevant/definitely useful/essential to assessment” for answering the basic questions. The remainder were either reviews or comments on other papers, or dealt more with fire characteristics, modelling, hydrology, rather than carbon, or were duplicating information in other references.

Results of text screening

Of the 110 references, 91 were from the UK or Ireland, including 10 from Scotland. 57 dealt specifically with muirburn, 16 with wildfire and 22 covered both. 23 were either completely or partially review articles. 96 were described as being on peat or peatland with only 5 as not being on peat or peatland. In terms of vegetation cover, 76 were on blanket bog or included areas of blanket bog, 8 included raised bog (only one was specifically on raised bog) and 9 were on either wet or dry heath. The time since burning generally covered 0 – 25 years but one considered 100 years and another 475 years. Management was mainly for grouse (27) with fewer for grazing (11) or both (18). Note that in the preceding, in some references the exact categorization was either not given, unclear or not applicable.

In the experimental set up, 49 included a comparative unburnt area, 28 included a time series and 27 covered repeat burning or burning intervals.

For the results, 32 reported the impact on vegetation. Carbon losses to soil by leaching were covered by 11 and to water courses by 26. Charcoal formation was covered by 7. Relatively few references specifically covered GHG emissions: 18 dealt with carbon dioxide and 5 mentioned methane.

Annex II. Glossary

Acrotelm	The upper layer within which the water table fluctuates
Black carbon	Product of burning, similar to soot, fine material
Blanket bog	Peat bog that covers the hills
Bulk density	Density (weight/volume) of soil or peat, usually on a dry weight basis
Calluna	Calluna vulgaris, heather, ling
Carbon dioxide	Main form of carbon in the atmosphere, main GHG
Carbon sequestration	Process whereby carbon is fixed into vegetation and soil for some appreciable time (years, decades)
Carbon turnover	Process whereby carbon is sequestered and then lost from vegetation and soil, carbon cycling
Catchment	Area of land where all the rainfall feeds into a single river
Char	Product of burning, referring to partially burnt vegetation
Charcoal	Product of burning, where lack of oxygen results in incomplete combustion of vegetation, generally coarse material
Chronosequence	Series of sites or plots representing a treatment applied over different times
Cool burn	A burn where only above ground leaves, thin stems and loose litter is consumed, thick stems remain
DOC	Dissolved organic carbon, soluble organic compounds from decayed vegetation that may be lost in streams and rivers
Emission	Loss of gases from vegetation/soil into atmosphere
Eriophorum	Sedge, common in peatland vegetation
Flux	Movement or exchange of material, usually gases, both to and from the vegetation/soil
Greenhouse gases	Gases in the atmosphere that lead to global warming, principally carbon dioxide, methane and nitrous oxide
Grips	Drainage ditches cut into peatlands
Hot burn	A burn where most above ground and surface vegetation, along with some surface litter, is consumed
Litter	Dead plant material ,which is still recognizable as such, and sits on the soil/peat surface
Methane	Gas containing carbon produced in water-logged soil/peat where oxygen is absent
Molinia	Purple moor grass, poorly palatable grass, nutrient poor but resistant to burning

Moorland	Treeless vegetation, typically heather though not always, covering the hills and uplands
Muirburn	The controlled burning of moorlands
Muirburn cycle	The time between successive muirburn events
NEE	Net Ecosystem Exchange, the difference between carbon dioxide fixed during photosynthesis and that lost in respiration
Nitrous oxide	A GHG lost from soil during the decomposition of nitrogen-containing compounds
Peat	Partially decayed plant material which accumulates in water-logged soil
Peat haggs	Residual mounds of peat surrounded by deep gulleys of eroded peat
Peat soil	Soil where the peat has accumulated to at least a depth of 50 cm
Peatland	Area covered in peat soil or having a peat-forming vegetation
Photosynthesis	Process whereby plants fix carbon dioxide from the atmosphere
Plant respiration	Process whereby plants lose carbon dioxide
POC	Particulate organic matter, finely divided organic material carried in water courses
Pyrogenic carbon	Covers various forms of carbon (black carbon, char, charcoal) formed during burning
Raised bog	Peat bog that forms in valleys and depressions
Soil erosion	Process where soil/peat is lost, either taken away by water or by wind
Soil organic matter	Carbon-containing material, the product of plant decay, includes peat
Soil respiration	Carbon dioxide lost from soil as the product of decomposition or decay
Sphagnum	A moss, a major peat-forming type of vegetation
Water table	The depth in peat or soil the zone below which is saturated in water (water-logged)
Wildfire	Uncontrolled fire which may be started naturally, accidentally or deliberately