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Understanding carbon sequestration in upland habitats

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1 Executive summary

1.1 Key findings

This project set out to review the current state of knowledge on the potential for carbon sequestration in key Scottish upland open habitats. Upland soils play a vital role in regulating greenhouse gas (GHG) emissions in our environment. Scotland's soils contain 2500-3500 Mt of carbon, much of which is located in upland soil environments. This is equivalent to more than 200 years of Scotland's annual greenhouse gas emissions. The management of uplands and their soils will therefore be critical to achieving Scotland's ambitious net-zero emissions target.

Despite the well-known potential of soils to store carbon, however, there is uncertainty as to the long-term stability of this carbon pool. Increasing temperatures, altered patterns of rainfall distribution, and changes in land use all influence this process and threaten to reduce soil carbon stocks.

This review identifies the key drivers of change including: climate change; nitrogen deposition; changes in atmospheric carbon dioxide concentrations; and local land management factors such as grazing by sheep and deer, and burning to maintain habitat and vegetation quality for grazing animals and grouse. It covers three upland habitats: upland dry heath, upland wet heath and upland grasslands, defined by vegetation communities. It assesses potential GHG fluxes and the impact on biodiversity within these habitats.

The evidence review found very limited information regarding impacts on soil carbon stocks or GHG emissions; studies giving a full balance sheet of ecosystem stocks and flows of carbon in response to environmental or management change were particularly scarce.

What do we know about carbon stocks in open upland habitats in Scotland?

- Upland habitats cover around 40% of the land area of Scotland. Current available datasets do not have full national cover at the required detail. It is therefore not possible to quantify the areas covered by upland dry and wet heaths, and by *Molinia* grassland.
- Scotland's soils contain around 2,500-3,500 Mt of soil organic carbon. The various mineral, organo-mineral and organic soils found under moorland, montane, and rough grassland contain around 45% of total Scottish soil organic carbon stock.
- Soil organic carbon accounts for 90% of the carbon stocks in these habitats. Therefore, studies which only consider changes in carbon held within the vegetation severely under-estimate changes in total carbon stocks.

- Measurements of soil organic carbon stocks at 183 National Soil Inventory of Scotland sample locations show that wet heaths contain greater organic carbon stocks per unit area than dry heaths (mean 313 t ha^{-1} compared to 205 t ha^{-1}).
- There is evidence from the National Soil Inventory of Scotland that, overall, soil organic carbon stocks in open, upland habitats did not change during the 25 years prior to 2007. However, there were no data on management practices available. It was therefore not possible to assess the positive or negative effect of management practices on soil organic carbon stocks.

What do we know about greenhouse gas emissions from open upland habitats in Scotland?

- GHG emissions in open upland habitats in Scotland occur as a result of emissions of carbon dioxide, methane and nitrous oxide. There is very little spatially explicit data on the net GHG balance from upland dry heath, wet heath or *Molinia* grasslands.
- Knowledge of the dominant biophysical processes suggests that, when in good condition, the cycling of CO_2 tends to be in equilibrium (i.e., uptake is roughly equivalent to losses) in these habitats. However, methane emissions will change as a function of drainage and rewetting. The presence and health of *Sphagnum* in wet heath habitats will also impact on the overall GHG emissions from these habitats.

What do we know about the relationship between biodiversity and carbon sequestration?

- The strongest evidence was found for upland dry heath. It has been shown that increases in grazing reduces the vegetation carbon stock and that burning has a neutral effect on carbon stored in the vegetation due to the rapid regrowth following managed burning. The effect of the removal of grazing on vegetation biodiversity is very site specific. We found no studies to show the impacts on other aspects of biodiversity.
- There is some evidence from Scotland that *Molinia* grasslands contain large carbon stocks within the vegetation, which are reduced by grazing.
- For both upland wet heath and *Molinia* grasslands, evidence for the effects of grazing, burning, nitrogen deposition or climate change on carbon stocks and biodiversity is extremely limited, with few consistent responses observed. There have been no studies in Scotland.
- When upland soils are left bare after excessive grazing or burning, there is a significant increase in the risk of soil carbon loss due to erosion.
- The impacts of future climate change on carbon stocks are complex and are likely to depend on current and future management, soil type and vegetation communities. They have not been well researched in the Scottish context: this is a substantial gap in knowledge.
- Dry upland heathland can undergo a transition to grassland as a result of heavy grazing or reduction in burning management. There is good evidence from site-specific studies in Scotland and northern England that this transition reduces carbon sequestration and carbon stock within the vegetation and top 15 cm of soil. . Restoration of heathland vegetation in degraded areas typically provides both a carbon and biodiversity benefit.
- The review found an important knowledge gap on the interactions of drivers on GHG emissions, carbon stocks and biodiversity.

1.2 Summary tables

Table 1: Summary of the evidence found on the direction of change of above ground carbon stocks, soil organic carbon stocks, atmospheric GHG fluxes and biodiversity as a result of different pressures for upland dry and wet heath and upland grassland habitats. Where there is more than one arrow, there are studies that show differing results. The darker the arrows the more confidence there is in the results.

There will be interactions between these drivers, but the literature reviewed did not provide the evidence to make an assessment of these interactions.

		Drivers of change						
Habitat	**Parameter**	**Grazing**	**Burning**	**Nutrient addition**	**Atmospheric deposition**	**Changes in atmospheric GHGs**	**Drought**	**Warming**
Upland dry heath	Above-ground C stock	↑↓ (black)	→ (black)	↑→ (black)	↑↓ (grey)	↑→ (grey)	↑↓→ (grey)	↑↓→ (grey)
	Soil C stock**	→ (white)	→ (white)	?	↑ (white)	?	↑↓ (white)	↑ (white)
	Atmospheric GHG flux	↑ (white)	↑ (white)	↑ (black)	↑ (grey)	?	↑ (grey)	↑ (grey)
	Biodiversity	↑↓ (grey)	↑↓ (grey)	↑↓ (grey)	↑↓ (grey)	?	?	?
Upland wet heath	Above-ground C stock	→↓ (grey)	↓ (grey)	↑ (white)	?	?	?	?
	Soil C stock**	?	→ (white)	?	?	?	?	?
	Atmospheric GHG flux	↑ (white)	↑ (white)	↑ (black)	↑ (grey)	?	↑ (grey)	↑ (grey)
	Biodiversity	↓ (white)	↑ (white)	?	↓ (white)	?	?	?
Upland grassland	Above-ground C stock	↓ (grey)	?	↑↓ (white)	↓ (white)	?	↑↓→ (white)	?
	Soil C stock**	↑↓ (white)	?	?	→ (white)	?	?	?
	Atmospheric GHG flux	↑ (white)	↑ (white)	↑ (black)	↑ (grey)	?	↑ (grey)	↑ (grey)
	Biodiversity	↑↓→ (black)	?	↓ (white)	↓ (white)	?	?	?

**** Assumption that vegetation cover is maintained, and the soil has not been left bare. In the latter case, the risk of erosion and therefore carbon loss significantly increases**

High confidence	Moderate confidence	Some evidence	
⬆	⇧	⇧	Increases
⬇	⇩	⇩	Decreases
➡	⇨	⇨	No change
	?		Lack of evidence

Table 2: Summary of findings on carbon stocks, greenhouse gas emissions and links between carbon sequestration and biodiversity in upland habitats

	Evidence	Knowledge gaps
Soil Carbon stocks		
Total extent and Carbon stocks	The total extent and total soil carbon stocks as a proportion of the national soil carbon stock is quantified but there is more uncertainty in total stocks in individual habitats due to the resolution of the mapping of vegetation communities.	Improved resolution of land cover data would improve the ability to calculate total stocks by habitat.
Stocks per unit area in habitats	The relative importance of soil carbon stocks in upland dry and wet heath is well established as data is Scotland specific and derived from the systematic National soil Inventory of Scotland.	There are not enough data to extract the impacts of specific management practices on soil carbon stocks in these habitats.
Soil versus vegetation stocks	Scotland specific data suggest that a very small proportion of carbon in upland habitats is in the vegetation compared to the soil suggesting that a priority should be in protecting SOC stocks.	
Evidence for C stock changes	Repeat surveys suggest that SOC stock in the uplands hasn't significantly changed in the last 25-30 years.	National scale surveys reflect the global drivers of change but there is insufficient data on land management between the repeat samples to assess if there are changes as a response to management.
Bare soils	When upland soils are left bare after excessive grazing or burning there is a significant increase in the risk of soil carbon loss due to erosion. This can be estimated by measuring the changes in thickness of organic horizons .	There is a lack of data in upland habitats by which to quantify these potential losses.
Greenhouse gas (GHG) emissions		
GHGs	Upland habitats produce carbon dioxide, methane and nitrous oxide emissions. In good condition the cycling of CO_2 tends to be in equilibrium in these habitats.	Quantification of full GHG emissions from these habitats is a knowledge gap and has implications for the calculations included in GHG inventories.
Differences in habitat types	The presence and health of *Sphagnum* in wet heath habitats will impact on the overall GHG emissions from these habitats. Methane emissions will change as a function of drainage and rewetting.	There is a lack of spatially explicit data from these habitats to quantify the differences in GHG emissions and the relative importance of individual GHGs in these different habitats
GHGs and climate change	An understanding of the processes occurring in upland habitats suggests that increasing temperature and frequency of drought as a result of climate change are likely to increase greenhouse gas emissions.	There is a lack of spatially explicit research in these habitats to allow potential interactions and changes to be quantified.
GHGs and land management	There is an understanding that carbon losses and GHG emissions due to grazing and burning can be offset to some extent by the more rigorous regrowth of vegetation, however this depends on the intensity of the burn.	There is a lack of spatially explicit research and monitoring studies to quantify the impacts of land management on GHG emissions.
Biodiversity		

Grazing and Burning	The impacts of grazing on biodiversity will depend on the intensity of the grazing prior to removal. The impacts of burning on biodiversity will depend both on the species composition of the habitat prior to burning and the intensity of the burn.	There is a lack of data on the impacts of grazing on wet and dry heaths compared to upland grasslands.
Climate change	There is an understanding that both changes in temperature and increases in drought conditions will change species composition in the long term but the impact in these habitats is unknown.	Determining the full impact of climate change on biodiversity will require long-term monitoring data.
Interactions	Many of the pressures reviewed will have differing impacts on biodiversity and carbon stocks and these are likely to interact, with different impacts depending on the current species composition and nature of the soils and soil hydrological conditions.	An important knowledge gap is the lack of studies on interactions of drivers on these habitats

Contents

2 Background

This section provides a description of the processes occurring in upland habitats.

Upland habitats cover around 40% of the land area of Scotland and are predominantly managed ecosystems consisting of vegetation communities which result from active management including burning and extensive grazing (Thompson et al 1995). They occur on a wide range of soil types including peat and support a wide range of biodiversity. Carbon stocks in these habitats are large, particularly in the soils, which often have a peaty (organic) surface layer.

Like with other soil/ plant systems, greenhouse gas (GHG) emissions from these habitats result from cycling of carbon and nitrogen by plants and soil organisms. GHGs, including carbon dioxide, methane and nitrous oxide, can be emitted, depending on the vegetation type, land management and soil wetness conditions. Carbon can also be lost in particulate form. This is caused by soil erosion or through being dissolved and leached as water flows through the soil, being emitted back to the atmosphere as carbon dioxide or methane (Figure 1). These can be particularly important loss pathways in cases where vegetation has been lost and the soil is left bare.

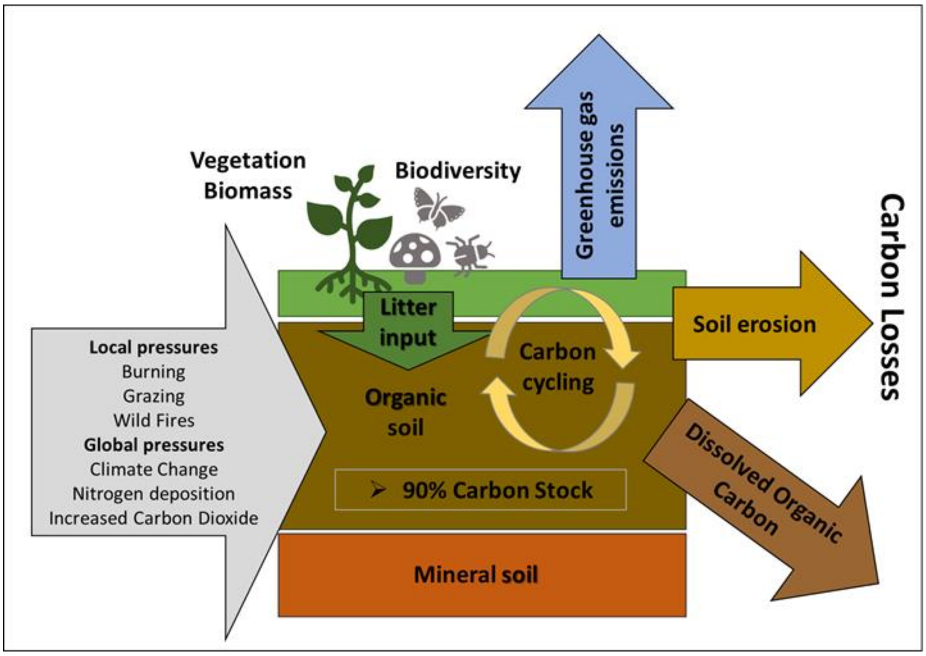

Figure 1: Upland habitats, pressures, carbon cycling and greenhouse gas emissions

3 Pressures and carbon cycling in upland habitats

This section provides a description of the pressures in upland habitats.

In this review we outline the characteristics of Scottish upland heathlands and grasslands when in good condition and summarise the known impacts of management and other pressures on carbon stocks and greenhouse gas fluxes in these habitats (Figure 1). We also consider the potential consequences of management for carbon stocks on biodiversity (but note that we do not review all known impacts of habitat management on biodiversity in these ecosystems, only the evidence for biodiversity change in relation to carbon stocks). Specifically, we addressed the following three questions:

- What do we know about carbon stocks in open upland habitats in Scotland?

- What do we know about greenhouse gas emissions of open upland habitats in Scotland?
- What do we know about the relationship between biodiversity and carbon sequestration?

The three Scottish upland habitats covered in the review (see Appendix 1 for detailed descriptions) are:

- Upland dry heath: dominated by heather and other shrub species and often found on dry, acidic soils with an organic surface layer.
- Wet heath: dominated by heather and *Sphagnum* mosses and usually found on soils with a wet or waterlogged, acidic organic surface layer.
- *Molinia* grassland: dominated by purple moor grass, typically found on wet, acidic soils.

Please note that the Blanket Bog habitat is outside the scope of this review

4 Upland habitats

This section provides a description of the vegetation communities, soils and what is known about the extent of upland habitats in Scotland.

To quantify carbon stocks and GHGs in upland habitats, detailed information is required on the extent of these habitats, the nature of the vegetation within them and on the carbon stocks, acidity, chemistry and drainage of the soils. Changes in vegetation communities can impact both the carbon cycling (as a result of changes in the plant matter which enters soil as litter) and the biodiversity in these habitats. The following section describes each of the habitats in terms of their extent, vegetation and soil typeswhich often includes peat, defined as soils with a surface organic horizon greater than 50 cm depth.

4.1 Upland dry heath

The plant community in upland dry heath is dominated by dwarf-shrubs. The most abundant is common heather which often occurs in combination with blaeberry, bell heather and crowberry. It is found on a range of soil types which have organic surface horizons. Mosses and lichens typically dominate the understorey, the layer of vegetation beneath the main canopy (Figure 2). Nearly all dry heath is semi-natural, being derived from woodland through a long history of grazing and burning (Rodwell 1991). Most dry heaths are managed as extensive grazing for livestock or as grouse moors. Dry heath in good condition has a low cover of grasses. However, if grazing or burning are too intense, or nitrogen deposition is high, then the heather can be replaced by upland grass species.

At higher elevations, above the potential tree line (ca. 800 m in eastern Scotland, lower in the west) a variety of natural dry heath communities occur in what is known as the alpine zone (Figure 2). These may be dominated by heather, crowberry, blaeberry or cowberry according to topographic location and the prevailing climatic conditions. The dwarf-shrub canopy becomes shorter as elevation increases and, when in good condition, lichen species (particularly in the east of Scotland) or mosses (particularly in the west of Scotland) are co-dominant. These communities may be extensively grazed by sheep and deer but are not generally intensively managed. As for upland heathlands, excessive grazing or trampling may result in reduction of dwarf shrub cover and replacement by grasses or in extreme cases to areas of bare soil, increasing risk of erosion.

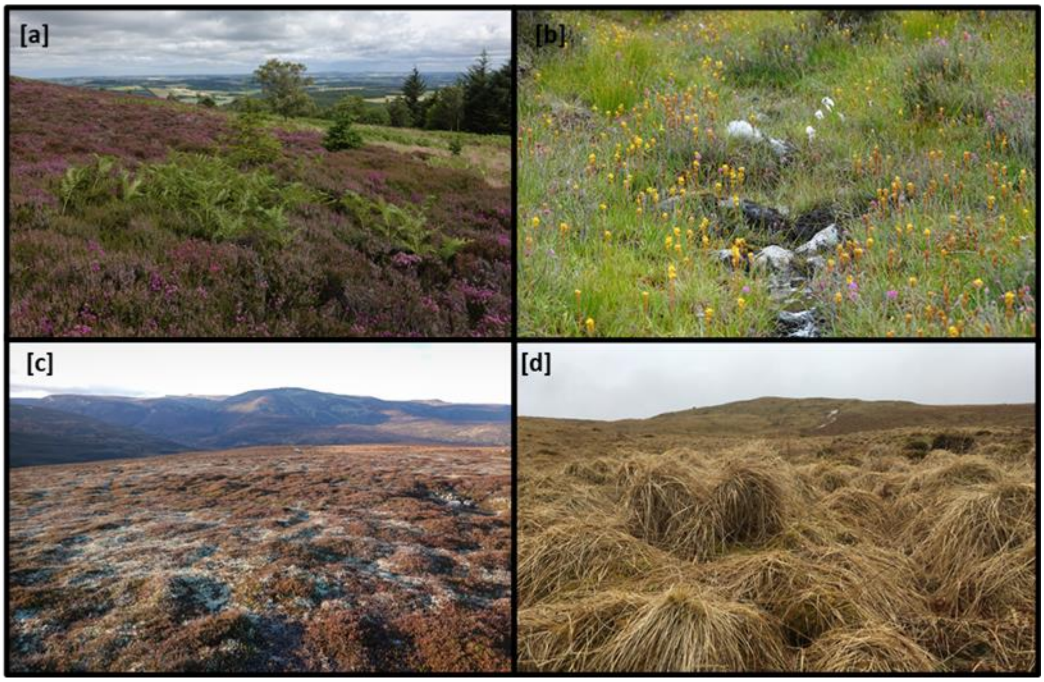

Figure 2: Example pictures of habitats featured in this report: (a) upland dry heath with invading bracken, (b) wet heath with flowering cross-leaved heath and bog asphodel, (c) alpine heath and (d) *Molinia*-dominated grassland. Photos: Andrea Britton and Debbie Fielding

4.2 Upland wet heath

Upland wet heath usually occurs on wetter soils with an organic surface layer. The vegetation is typically dominated by mixtures of cross-leaved heath, common heather, deer grass and *Sphagnum* bog-mosses (Figure 2). Upland wet heath is generally a semi-natural community derived from woodland and blanket bog through a long history of burning and grazing (Rodwell 1991). Wet heath in good condition has only a moderate cover of grasses such as purple moor grass and a low cover of rushes.

4.3 *Molinia* grassland

In Scotland, *Molinia* grasslands are usually considered as being derived from wet heath that has been subject to high levels of grazing and burning (Rodwell 1991) and, as such have similar soil types. They have high cover of purple moor grass (*Molinia caerulea*) with varying contributions of rushes, cross-leaved heath, common heather, deer grass and *Sphagnum* bog-mosses (Figure 2). On more nutrient rich sites, a mire develops with a higher representation of rushes and tall herbs such as marsh thistle. This vegetation is likely found on sites derived from wet woodland and usually has a higher plant diversity than the *Molinia*-dominated sward derived from wet heath (Rodwell 1991).

4.4 Habitat extents

The extent of these habitats is mapped nationally by the EUNIS Land Cover of Scotland (NatureScot 2015, Figure 3), which is based on Land Cover of Scotland 1988 (LCS88), corrected for forestry using the National Forest and Native Woodland Inventories (Appendix 1). From the data sets currently available at a national level, it is not possible to quantify the individual areas of upland dry and wet heaths, and *Molinia* grassland. The combined area of these habitats is around 31,000 km^2, with a combined area of wet and dry heath of approximately 19,933 km^2 plus an additional unknown area of alpine heathland included in the montane category (Figure 3). Data from LCS88 suggests an area of *Molinia* grassland of around 3,472 km^2 but with additional unquantified area of *Molinia* grassland which forms part of the area mapped as 'undifferentiated heather moor'. A portion of the other grassland habitat types may also represent grasslands derived from degraded upland heathland habitats.

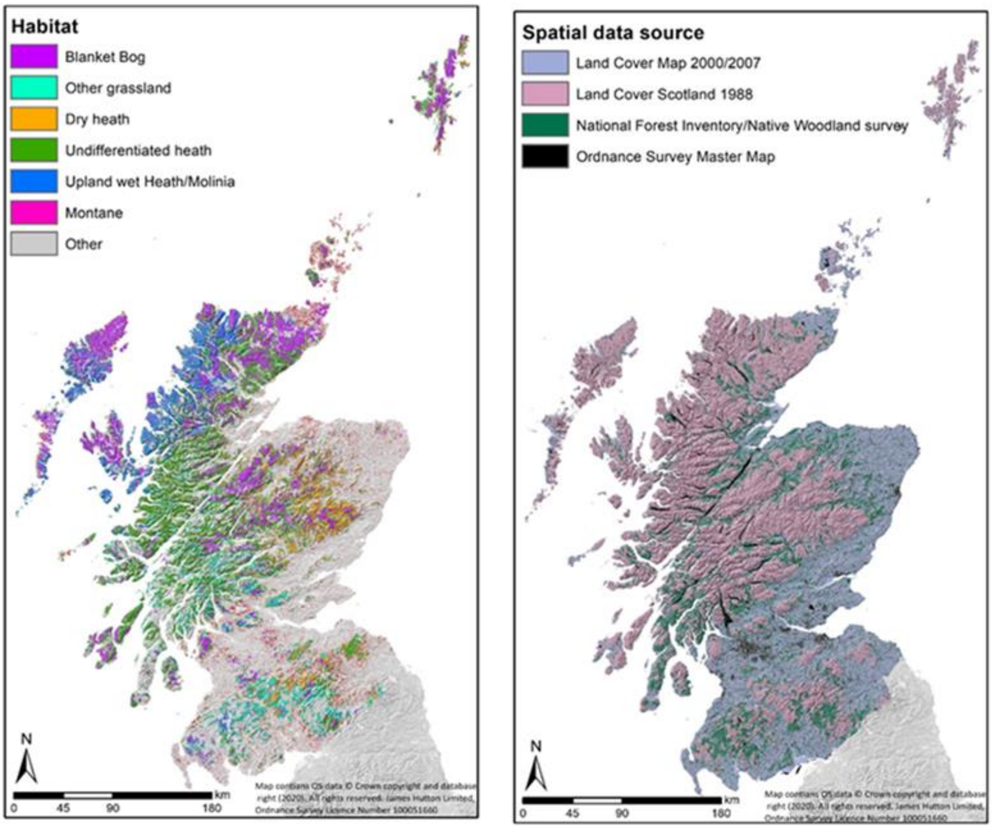

Figure 3: EUNIS Land Cover of Scotland showing upland habitats and blanket bog and the sources of data from which the habitat map was derived (Nature Scot., 2015)

4.5 Upland management

In Scotland The dominant land use in these habitats is sheep and deer grazing and around 10,094 km^2 of land holdings include active management for grouse shooting (Matthews et al 2018). Land management for grouse, and sometimes also for sheep and deer, requires burning of vegetation to control invasion by scrub and to maintain habitats in a suitable condition for ground nesting birds. Management of vegetation for sheep and deer grazing may also involve burning to remove old, woody vegetation and to encourage fresh plant growth with a higher nutritional value for grazing animals . Burning practices vary and, depending on how it is conducted, fire may help to maintain dense stands of vigorous heather or encourage conversion of heathland to grassland. These management practices have evolved without necessarily considering potential losses of carbon from these habitats. In addition to livestock management, upland habitats are increasingly being utilised for forestry and renewable energy production, although the impacts of these activities are outside the scope of this project.

In addition to management pressures, upland habitats are also subject to the global environmental pressures of climate change and atmospheric deposition (when pollutants fall from the air to the earth's surface). We are already witnessing impacts from a changing climate; There is evidence of increased temperatures as well as altered amounts and patterns of precipitation, resulting in changes in snow cover and increasing drought frequency (Murphy et al 2019). Atmospheric pollution from the deposition of sulphur and nitrogen increased greatly following industrialisation. Although sulphur emissions have been controlled by legislation, nitrogen emissions are less well controlled; nitrogen deposition has not shown the same magnitude of declining trend (Britton et al 2011, RoTAP 2012).This is important: changes in soil and vegetation chemistry can alter the way carbon is cycled in these habitats and the amount of carbon lost as greenhouse gases are leached as dissolved organic carbon. In addition, changes in carbon dioxide concentration in the atmosphere, as well as driving climate change, can increase plant growth and change the carbon cycling in these habitats.

5 Soil organic carbon stocks

This section provides a review of the information on the quantification of soil organic carbon (SOC) in upland habitats in Scotland and evidence of change. It outlines the SOC stocks and the proportions of carbon stored in the soil and vegetation of each of the three habitats described above. We also present the evidence for change in SOC stocks at a national level based on Scottish and UK sampling.

Considerable work has been done to both estimate (Baggaley et al 2016) and measure (Chapman et al 2013) carbon stocks in Scotland's soils. Baggaley et al (2016) estimated that Scotland's soils hold between 2,500 and 3,500Mt of carbon in the upper 100 cm. This is 60 times greater than the carbon stocks in all vegetation, including forestry (NatureScot, 2020). Soil carbon stocks in rough grassland, montane and moorland habitats account for around 45% of the total soil carbon stock (Baggaley et al 2106), and data show that between 87% and 95% of the carbon stored in these habitats is in the soil (Britton et al 2011).

SOC stock is calculated by the multiplication of measured soil bulk density (corrected for stone content), carbon concentration and horizon depths. The National Soils Inventory of Scotland (NSIS) data (Chapman et al 2013) provides direct measurement of all these factors, allowing the calculation of the soil carbon stocks to 100 cm depth at 183 equally spaced sites throughout Scotland at 20km apart. The vegetation community is also recorded at each of these sites allowing direct comparison of carbon stocks between habitat types (Figure 4).


Figure 4: Soil profiles typical of wet heathland (left) and of dry heathland (right) showing dark organic layers at the surface and lighter coloured mineral layers below.

These data show a greater mean carbon stock per hectare in soils under wet heath compared to soils under dry heath (Table 3). There were too few soils sampled under the *Molinia* grassland habitat type to make similar comparisons.

As factors such as organic carbon concentration and bulk density are less likely to vary between these carbon-rich, surface organic layers, the difference in average carbon stock between upland dry heath and wet heath is most likely due to the greater average thickness of the carbon-rich, surface organic layer found in soils under wet heath. Using the data from the National Soil Inventory of Scotland, the average thickness of the organic layer under wet heath vegetation types was 41 cm (range 10-110 cm) and 23 cm (range 4-118 cm) thick in upland dry heath (note, peat soils were found under both these vegetation types).The greater average thickness of the organic layer in the soils under wet heath is consistent with prolonged wetness that inhibits the breakdown of the plant-derived organic matter.

Table 3: Soil organic carbon stocks to 100 cm by habitat derived from the National Soil Inventory of Scotland data (2007-2009)

Habitat	Sample number (n)	SOC stocks to 100 cm [t/ha]		
Habitat	**No. Points**	**Mean**	**Min**	**Max**
Upland Dry Heath	19	205	47	648
Wet Heath	22	313	114	784
***Molinia* grassland**	3	237	203	281
Other Grasslands with *Molinia**	8	337	99	823

* these vegetation communities include those with both *Molinia* and *Nardus* species, and *Molinia with bracken.*

The evidence for changes in SOC stocks over time comes from repeated surveys of these stocks. Data from the repeat survey of the National Inventory of Scotland (Chapman et al 2013, Lilly et al 2010 & 2011) undertaken in 2007-2009 showed no statistically significant change in soil organic carbon stocks to a depth of 100 cm in all habitats including cultivated land with an average time between the original and resampled soils of 25 years. Only forested land showed any increase in SOC stocks. Subsequent analysis of the SOC stock data for dry upland heath, wet heath and *Molinia* grassland habitats also showed no significant change between the inventories.

A similar repeat survey of over 5,000 inventory sites in England and Wales (Bellamy et al 2005) showed that soils under upland grassland and moorland had lost soil carbon in the upper 15 cm in the period between the surveys. However, Smith et al (2007) suggested that the sampling methodology used by Bellamy et al. (2005) could lead to errors where the organic layers were relatively thin, such that varying amounts of underlying mineral material could be incorporated into the sample.

The Countryside Survey (Emmett, et al 2010) has 195 locations where soil carbon has been measured in Scotland across all habitat types. However, this survey also only measured carbon concentration in the top 15 cm of the soil profile. Analyses showed that there was no change in carbon concentrations in acid grasslands and dwarf shrub heath between 1978 and 2007 (Reynolds et al 2013).

All these national scale sampling campaigns assess the impacts of global drivers of change such as nitrogen deposition or climate change, but they all lack information on the land management employed between sampling dates. The data do not allow us to separate the effects of global drivers of change (climate, nitrogen deposition) from local scale management effects (e.g. compaction from overgrazing or erosion from bare soils due to burning or overgrazing).

The lack of information on the spatial extent of the broad habitat classes of upland wet heath, dry heath and *Molinia* grassland means it is not possible to determine the total amount of organic carbon stored in the soils under each of these habitat types.

While we can quantify change in soil organic carbon concentrations and stocks through time, there is insufficient evidence from soil inventories to determine the impact that land management has had on soil organic carbon stocks. While the evidence shows that there has been little overall change nationally in the carbon organic stocks in these habitats over the last three decades, changes may have occurred at individual sites.

6 Greenhouse gas emissions and nutrient loss

This section presents evidence for the nature of GHG fluxes in upland habitats and factors that may influence emissions. Very few studies were found regarding impacts of pressures on soil carbon GHG fluxes. Estimates of fluxes are often derived from what is known about lowland environments or other systems such as blanket bog, with very few measurements in open upland habitats.

We describe how carbon is processed in upland systems and what can be lost through leaching and as greenhouse gases. Loss of carbon associated with runoff / erosion process that may derive from degradation of soil surface are not discussed here. It describes what we know about carbon cycling processes and about how these processes might change as a result of global change and local management actions (grazing and burning). It then outlines the gaps in the information required to quantify carbon cycling and hence the potential for change.

Upland soils play a vital role in regulating greenhouse gas emissions in our environment. As noted earlier in this report, Scotland's soils contain 2500-3500 Mt of carbon, much of which is located in upland soil environments. This quantity of carbon is the equivalent of more than 200 years of annual emissions of GHG from the whole Scottish economy. However, much of this carbon is relatively stable and, without land-use change, changes in the storage of carbon only happen over a long period of time. Carbon is added to soils through the input of plant material and it is lost by the processes of respiration and leaching (Figure 1). In circumstances where the annual addition is equal to losses, the carbon content of the soil will remain constant. However, if carbon input exceeds losses then the soil will be a net sink for carbon, a process known as carbon sequestration. In mineral soils the rate of sequestration tails off through time (Poulton et al., 2018) and in organic and organo-mineral soils the main mechanism for increasing carbon stocks is through increasing the thickness of the organic soil horizon. Minasny et al.,2018 suggest that in regions where soils have high inherent soil organic carbon contents they may have already reached an equilibrium and without climate or land use change carbon losses are balanced by gains. The main process of loss of carbon from soils is soil respiration which results in the release of carbon in the form of carbon dioxide to the atmosphere. GHG inventories report little release of carbon dioxide from upland soils despite their large carbon stocks because of their stability or resistance to change. This reflects the fact that the natural nutrient cycling processes resulting in carbon dioxide loss from soils are largely balanced by uptake by the vegetation. However, carbon released from soils as carbon dioxide is not the only greenhouse gas produced. Nitrous oxide and methane emissions can occur from these soils and can make a significant contribution to overall GHG emissions.

Nitrous oxide is a powerful greenhouse gas with a global warming potential that is 264 times greater than carbon dioxide and is released following the addition of nitrogen fertilisers or animal manures to soil. Methane has a global warming potential of 34 times greater than carbon dioxide and is released from ruminant livestock and wetland soils. For the purposes of inventory reporting (which reports on human-induced greenhouse gas emissions) methane emissions are only reported from wetland soils that have been altered from their natural condition. While methane and nitrous oxide tend to be emitted in smaller quantities than carbon dioxide, their impact as greenhouse gases is magnified by their higher warming potential However methane persists in the atmosphere for a shorter period of time, meaning that short term increases or decreases in methane emissions can lead to rapid changes to the warming of our climate.

6.1 Upland dry heath

6.1.1 What we know

Carbon storage and loss in upland habitats dominated by heather is subject to the effects of local topography and interaction between various soil, climate, and management factors. Although heathland soils exchange carbon dioxide and methane with the atmosphere, this is mostly considered to be a result of natural processes and is therefore not reported as human-induced GHG emissions in UK national emissions reporting.

However, these habitats are extensively managed so the emissions recorded in the inventory will be generally limited to methane emissions from ruminant livestock and therefore much smaller than for intensive agricultural production systems in lowland areas.

Methane fluxes from soils depend primarily on soil moisture; waterlogged soils emit methane while drier mineral soils produce little or no methane. Dry heaths would therefore be generally associated with low methane emissions.

In addition, one study has indicated a broad range of values for upland dry heath from a net source releasing 34 g carbon/ m^2 /year to a net sink sequestering 146 g carbon/m^2 /year (Farage et al 2009). One of the factors influencing carbon fluxes in these environments would be heather burning. Burning events cause an immediate loss of the carbon contained in plant material, and extreme burning can lead to some carbon loss from the soil surface. However, burning losses in the plant material can be offset by rapid regrowth of the vegetation and the subsequent uptake of atmospheric carbon dioxide. Accounting for this uptake burning has been shown to result in only a small overall change in net GHG emissions (Farage et al.2009). However, there is a lack of detailed studies on the carbon balance of dry heaths under different management regimes.

6.1.2 What we do not know

There is a lack of detailed studies of upland dry heaths in Scotland which quantify the full carbon budget or net GHG emissions in their current state or as a result of land cover or management change.

6.2 Wet heath and grasslands

6.2.1 What we know

These habitats are dominated by moss (primarily *Sphagnum)* under waterlogged conditions and may support carbon-rich soils. Their carbon sequestration potential depends on the dominance and succession stages of *Sphagnum* species. Due to waterlogging, these systems may represent a source of methane and may not always contribute to the net removal of carbon dioxide from the atmosphere. Emissions from wetland soils are only accounted for in inventory reports where they have been altered by human activity. This can result in reductions in methane emissions where wetlands are drained but increases in methane emissions following the re-wetting or drain blocking of peatland sites.

The full greenhouse gas balance of these systems is, however, complex. Generally, *Sphagnum* increases acidity and moisture content of their habitat and slows down decomposition rates, leading to accumulation of organic material (Harpenslager et al 2015). Carbon dioxide removal from the atmosphere in these systems is primarily through plant production. However, at the same time carbon dioxide and methane are emitted to the atmosphere as a part of the natural processes of plant and soil organic matter decomposition. Both carbon dioxide and methane can also be lost from wetland sites by transport in stream water. It was estimated at a wetland site in the south of Scotland that almost 25% of the carbon captured by plants through photosynthesis could be lost in drainage water in the form of organic carbon compounds (Dinsmore et al 2010).

6.2.1 What we do not know

As in the case of dry heaths, there is very little evidence for significant anthropogenic GHG emissions from grasslands and wet heaths. GHG inventories report relatively small emissions from these environments which result from grazing livestock and limited nitrogen inputs in the form of fertilisers and animal manures. However, our estimates of such emissions tend to be derived from experimental observations in lowland environments and may therefore under or over-estimate real emissions. The large carbon stocks contained in wet heaths make them susceptible to carbon loss both as a result of land use change and climate change. Climate change represents a particular threat given that the carbon that has accumulated in these soils has done so because of the climatic conditions (low temperature and high rainfall) which have been prevalent in these areas. It is anticipated that climate change will result in warmer and drier summers. This could lead to significant carbon loss, although this remains highly uncertain at this stage.

6.3 Greenhouse gas fluxes across habitats

6.3.1 Areas that are subject to active research and debate

Despite the potential of soils to store carbon, there is uncertainty in the long-term stability of this carbon pool in the face of climate change. Increasing temperatures, altered patterns of rainfall distribution and changes in land use threaten to reduce soil carbon stocks. This change could occur as a result of increased respiration in soils which releases carbon dioxide from the soil organic matter pool (Fang & Moncrieff 2001). However, the impact of climate change on soil carbon stocks is dependent on the net effect on uptake and removals and is an area of active research (Hewins et al 2018; Bradford et al 2016). Changes could also occur as a consequence of erosion linked to episodes of high rainfall and surface run-off. Further research and modelling are required in order to understand the potential extent and scale of any change.

6.3.2 What we do not know

The greenhouse gas balance of a system is the sum of losses and gains of GHGs from a given area. Upland soils represent some of the most complex and variable soil systems in which to estimate greenhouse gas balances. This is because not only are the soils highly heterogeneous, but also carbon dioxide and methane can be transferred between the soils and the atmosphere, and also through leaching in water (for example, as dissolved organic carbon).

Comprehensive accounts of the net greenhouse gas balance of upland systems would include measurements of the uptake and release of methane, nitrous oxide and carbon dioxide. However, this has so far not been undertaken extensively in Scotland. There is some evidence that the way carbon is transported out of the system may differ from arable or grassland agricultural systems. Similarly, studies of atmospheric exchange of carbon between peatland ecosystems and the atmosphere have demonstrated that sink strength is highly variable from year to year, and that climate change may well move habitats from a carbon sink to a carbon source (Helfter et al 2015). Thus, in order to fully understand the greenhouse gas balance, we need to quantify exchanges of carbon between the land and atmosphere as well as leaching losses. This has potential impacts for many of our upland soils in Scotland, as the stability of their carbon stocks may have high sensitivity to climate change which could impact on both atmospheric exchange and leaching.

7 Environmental and management impacts on carbon stocks

Most scientific studies which have investigated the effects of environmental change and habitat management activities on carbon stocks and fluxes in upland ecosystems have focused on above-ground carbon stocks in vegetation and plant litter. The evidence review found very limited information regarding impacts on soil carbon stocks or GHG emissions; studies giving a full balance sheet of ecosystem stocks and flows of carbon in response to environmental or management change were particularly scarce.

In the following section we summarise the available evidence for environmental and management impacts on carbon stocks and fluxes in each of the three focal habitats in turn. There is an important knowledge gap on the interaction of drivers. The greatest number of studies was found for upland dry heath, while information for upland wet heath and *Molinia* grassland was much more limited. Where there was no evidence available from Scottish field studies (which was often the case) we draw on evidence from comparable habitats elsewhere in the UK and Europe, and from laboratory and greenhouse studies which investigated the responses of key species associated with the focal habitats (e.g. heather or *Molinia*). While these studies can give an indication of the likely direction of responses of Scottish upland habitats to environmental and land management changes, the large gradients in important environmental factors, such as temperature and rainfall, across the UK and Europe mean that the magnitude and sometimes even the direction of response of Scottish habitats may differ. In general, more studies of carbon stocks and fluxes in Scottish upland heathlands and grasslands are required. These studies should cover the range of climates present from east-west and south-north, to gain an accurate picture of the current carbon stocks in these habitats, their sensitivity to losses and the potential to increase carbon sequestration through altered management.

7.1 Upland dry heath

7.1.1 What we know

Grazing

Upland dry heathlands are grazed by both domestic stock (mainly sheep but occasionally cattle) and wild herbivores (deer and small mammals). There is strong evidence from studies in both the UK and Europe that, within dry upland and alpine heathland communities, grazing pressure (from both wild and domestic animals) has a negative impact on above-ground biomass carbon stocks (Smith et al 2015, Rupprecht et al 2016, Sorensen et al 2018b, Riesch et al 2020). There is insufficient evidence however, to determine if wild and domestic grazers differ in their impacts on carbon stocks. A study of upland heaths in Scotland and England showed that removal of grazing by large herbivores increased above-ground carbon stocks by up to 50% but had limited effects on soil carbon stocks (Smith et al 2015). This response was modified by nitrogen deposition; sites receiving more than 11kg N ha^{-1} y^{-1} deposition showed an increase in soil carbon stocks when grazers were removed.

The removal of grazing from dry heathlands in Europe has been associated with both no change and decreases in vegetation species richness (Riesch et al 2020, Rupprecht et al 2016). This suggests that impacts of grazing removal on biodiversity are likely to be context dependent and will depend on the intensity of grazing prior to its removal.

Burning

Upland dry heathlands may be subject to controlled burning management, either to improve vegetation structure for ground-nesting birds (mainly grouse), or to increase food quality for grazing animals. They may also be subject to wildfires, which are typically more intense and cover larger areas. These two types of fires are distinct and may have very different effects on ecosystem carbon stocks and biodiversity.

Evidence for the effects of management burning on above and particularly below-ground carbon stocks in dry heathland is surprisingly limited. Studies of management burns on heathlands in the UK uplands suggest that <30-100% of the above-ground carbon stock may be lost during a management burn, while soil carbon stocks should not be impacted if the burn is properly managed (Kayll et al 1966, Farage et al 2009, Legg et al 2010, Worrall et al 2013). In most widespread dry heathland types, plants are not killed by management burns and burning may increase nutrient availability in the soil (Brys et al 2005). Rapid re-growth of vegetation following fire temporarily increases the rate of carbon sequestration into plant biomass, potentially resulting in neutral carbon dynamics over the whole fire cycle (Farage et al 2009, Legg et al. 2010). The size of the above-ground biomass carbon stock is positively related to time since fire, and reaches a maximum at around 20 years (Alday 2015). Both the amount of carbon lost during fires and the rate of carbon accumulation in biomass and litter following fire are impacted by variations in climate across the UK; carbon losses are greater, and biomass and litter accumulate more rapidly, under warmer, drier conditions (Davies et al 2016, Santana et al 2016). There is some evidence that, under certain conditions, well-managed management burns where the soil carbon stock is unimpacted may benefit carbon storage, as a small part of the burned biomass is converted to charcoal, which decomposes much more slowly than unburnt plant litter and forms a long-term, stable carbon store (Worrall et al 2013).

Management burning of upland heathland impacts significantly on biodiversity, as the vegetation structure changes markedly as heather re-grows following fire (Harris et al 2011). However, different groups of species respond differently to the fire cycle. In most widespread dry heathland communities, plant biodiversity peaks soon after burning and then declines as heather regains dominance. However, for some dry heathland types in western Scotland which are rich in mosses and liverworts, burning can lead to a long-term reduction in diversity as liverworts, in particular, are slow to recover from fire (Rodwell 1991). In terms of other species groups, diversity of moths and butterflies peaks in unburnt heathland, while burning has little impact on spider and beetle diversity (Usher & Smart 1988, Gardner & Usher 1989, Haysom & Coulson 1998, Davies & Legg 2008, Harris et al 2011).

Wildfires may be more intense than management burns and may remove both above-ground carbon stocks and a portion of the soil carbon store (Maltby et al 1990). Hot fires may kill the heathland plants resulting in slow regeneration of the vegetation following fire, and the potential for additional soil carbon losses due to erosion from bare soil surfaces (Maltby et al 1990). Wildfires generally have negative impacts on ecosystem carbon stocks. This may (as for management fires) be slightly offset by the formation of charcoal which acts as a stable long-term store for carbon if it is retained on site and not subsequently washed away (Clay & Worrall 2011). Overall, however, wildfires have the potential to cause large ecosystem carbon losses.

Nitrogen deposition

There is strong evidence from studies across the UK that nitrogen deposition at levels currently seen in the wider countryside (up to ca. 50 kg N ha^{-1} y^{-1}) has a positive effect on heather growth and litter layer mass (Lee 1998, Lee & Caporn 1998, Carroll et al 1999, Barker et al 2004, Britton et al 2008, Phoenix et al 2012, Jones et al 2012, Southon et al 2012, Field et al 2017). However, this effect may not persist in the long term if other nutrients start to limit plant growth, or if heather is left unmanaged and becomes degenerate, at which point its growth will slow. Hence, faster growth and litter accumulation may not necessarily lead to a larger carbon stock in the longer term. Quantification of carbon stocks in relation to nitrogen deposition has shown increases, decreases or no change in above-ground carbon stock but predominantly increased soil carbon stock at 0-15 cm depth with increasing nitrogen deposition (De Vries et al 2009, De Schrijver et al 2011, Southon et al 2012, Smith et al 2015, Field et al 2017, van Paassen et al 2020). This suggests that the effects of nitrogen deposition on above-ground carbon stocks are likely to be context dependent, while below-ground effects are likely to be positive. Similarly, mixed responses are reported for alpine dry heathlands dominated by Crowberry and Cowberry and Blaeberry in Scandinavia, with both increases and no change in above-ground carbon stock and increased soil carbon stock in response to increased nitrogen (Richardson et al 2002, Liu et al 2020).

The negative effects of nitrogen deposition on heathland biodiversity are well established (Bobbink et al.,2010). In dry upland heathlands, nitrogen deposition is particularly associated with negative impacts on the mosses and lichens that are both an important component of upland biodiversity and in the case of mosses, represent a significant proportion of the biomass carbon stock (Curtis et al 2005, Bobbink et al 2010, Britton & Fisher 2007, Britton et al 2011, van Paassen 2020). High nitrogen deposition may also cause a change in habitat from heather dominance to grass dominance (Bobbink et al 2010). These changes have implications for both biodiversity and carbon stocks because shrub biomass (e.g. heather) decomposes more slowly than grasses and can promote soil carbon storage (Quin et al 2015). Negative impacts on mosses and lichens and an increase in grasses are also seen in alpine dry heathlands in Scotland and Scandinavia; these are associated with a change in the biodiversity of insect herbivores (Richardson et al 2002, Britton & Fisher 2007, Liu et al 2020).

Changes in atmospheric GHGs

Only limited evidence on the effects of increasing carbon dioxide on heathland carbon stocks is available, including field studies in Europe and laboratory studies. Laboratory studies of heather and bracken growth under elevated carbon dioxide levels showed increased biomass in heather, but no change for bracken (Woodin et al 1992, Whitehead et al 1997). A Swiss field study found increased above-ground biomass in response to elevated carbon dioxide, while a Danish study found no effects above-ground but an increase in root biomass below-ground (Kongstad et al 2012, Arndal et al 2013, 2014, 2018, Dawes et al 2015). These mixed results suggest further research is needed to clarify the likely effects of elevated carbon dioxide in the Scottish context. The only evidence for impacts of elevated carbon dioxide on biodiversity was a reduction in mosses and lichens and increases in dwarf shrubs and grasses seen in the Swiss heathland (Dawes et al 2015).

Drought and temperature

Evidence for the effects of rainfall reduction (summer drought) and increased temperatures on heathland biomass and carbon stocks is only available from Wales and from pan-Europe studies. There is limited evidence to suggest that heathland response to drought is dependent on baseline rainfall. In a Welsh upland heathland with high rainfall, drought had no effect on above-ground biomass in the short term, but a positive effect in the longer term; at drier sites in Europe drought had a negative effect (Gorissen et al 2004, Wessel et al 2004, Penuelas et al 2004, 2007, Reinsch et al 2017). Below-ground responses to drought are also mixed. Response of below-ground plant biomass (roots) to drought varies between species (Arndal et al 2013, 2014). In Welsh heathland, persistent drought changed soils from a net sink of carbon to a net source (Sowerby et al 2010) but other studies suggest that effects of drought on soil carbon stock could be either positive or negative depending on the severity of the drought (Ritson et al 2017, Reyns et al 2020).

There is consistent evidence, from upland and alpine dry heaths in Wales and across Europe, that warming increases above-ground biomass, although the magnitude of responses is variable (Richardson et al 2002, Penuelas et al 2004, 2007, Wessel et al 2004, Andressen et al 2009, Michelsen et al 2012, Dawes et al 2015). In a Welsh upland dry heath, warming of 1°C increased above-ground biomass by 15% (Penuelas et al 2004, 2007). Evidence of warming effects on below-ground biomass is limited; root biomass of heathland grasses has been seen to decrease with warming while heather biomass variously increases, decreases or does not change (Andresen et al 2009, 2010, Arndal et al 2013, 2018). In the soil, there is some evidence that warming increases carbon losses through soil respiration and increased litter decomposition (Emmett et al 2004). The net effect of increased carbon sequestration above-ground vs increased carbon losses from the soil on the total ecosystem carbon stock remains unclear.

There is very limited evidence of biodiversity changes directly associated with drought and warming impacts on biomass and soils. Moss biomass was strongly reduced by drought and impacts on soil biodiversity were also reported in Denmark (Andresen et al 2009, Haugwitz et al 2014). While several studies show differential responses of plant species biomass to warming, there was no evidence of changes in plant diversity (Andresen et al 2009, Dawes et al 2015, Michelsen et al 2012). In general, however, water availability and temperature are important predictors of species' distributions. Drought and warming would thus be expected to have significant effects on biodiversity in the longer term.

7.1.2 What we do not know

There are many knowledge gaps around the impacts of environmental change and habitat management on carbon stocks in upland dry heathland, particularly in the Scottish context. In general, scientific studies have focused on plant responses to environmental change and habitat management, often just measuring plant growth or biomass. Carbon stocks are rarely quantified and full profile data for soils are particularly scarce. While soil carbon stocks measured by national scale studies such as soil inventories do not show long-term change, experimental studies show changes in carbon fluxes out of soil (losses of carbon as gasses or dissolved in water) in response to environmental drivers. We do not currently understand the reason for this difference. Key knowledge gaps in relation to each driver are listed below.

Grazing

Knowledge of the effects of grazers on below-ground carbon stocks is limited (there is only one study although this does include Scottish sites). Nor are there studies that have quantified changes in carbon stocks due to grazing over the full soil profile. In addition, there is insufficient information to distinguish between the effects of wild (deer, small mammals) versus domestic (sheep, cattle, horses) grazers or between different species of domestic grazers. To date, most studies have focused simply on presence or absence of grazing (by all species): there is no information on the separate effects of grazing, browsing and trampling on carbon stocks. The impact of grazing removal on above and below-ground carbon stocks or below-ground biodiversity over the long term cannot be fully quantified due to a lack of available data.

Burning

Most studies of burning impacts have focused on moorlands managed for grouse. There is a lack of data on the impact of fire on soil and vegetation carbon stocks and GHG emissions in the Scottish context and over the complete duration of the management cycle. In particular, data is lacking on the differences in impact between burning management for grazing, rotational burning for grouse and wildfire, especially over the whole soil profile.

There is a lack of data on the trade-off between management burning and wildfire risk to heathland carbon stocks under a scenario of reduced management burning in Scotland.

We know little about the separate effects of management burning (as opposed to total grouse moor management) on biodiversity, with evidence currently limited to a small number of species groups.

Nitrogen deposition

Information on the spatial variation in above and below-ground carbon stocks across Scotland in relation to nitrogen deposition is limited to a single study, with soil carbon stocks measured in the top 15 cm only. There are no data that cover the full gradient of nitrogen deposition in Scotland and quantify carbon stocks over the full soil profile.

We have limited understanding of the effects of nitrogen deposition on biodiversity beyond plants; more studies are required for other species groups.

Increased atmospheric carbon dioxide

Information on the implications of increasing atmospheric carbon dioxide concentration for above and below-ground carbon stocks or how this may influence biodiversity in heathlands is very limited, with no studies from the UK.

Change in rainfall and temperature

There are no data on the impact of drought on carbon stocks in dry heathland in Scotland; UK studies are limited to a single site in Wales. Assessment of both above-ground carbon stocks and full profile soil carbon stocks for the range of climatic conditions found in Scotland is an important knowledge gap.

There is no information on how the effects of drought on heathland vegetation might impact other elements of biodiversity, particularly over the longer term.

There are no data on warming effects on above and below-ground carbon stocks in Scottish heathlands or how warming induced changes in heathland vegetation might impact on wider biodiversity. UK studies are limited to a single site in Wales; and most studies quantify plant growth, biomass and soil respiration fluxes only. Data on the sensitivity of existing soil carbon stocks to warming are particularly important but are currently lacking.

7.2 Upland wet heath

7.2.1 What we know

Grazing

Evidence for grazing impacts (of wild or domestic animals) on carbon storage in upland wet heath is very limited. Studies of wet heath in northern England have shown both no impact of long-term low-intensity sheep grazing on above-ground biomass (Alday et al 2015) and increased above-ground biomass with grazing reduction (Hulme et al 2002). Effects of grazing on above-ground biomass may be context dependent, but more studies are required to confirm this.

There is limited evidence on the effects of grazing on biodiversity in wet heath. Two studies in northern England showed that shrubs, mosses and sedges benefitted from grazing removal. Overall plant diversity was increased, while grasses including *Molinia* and mat-grass were reduced (Hulme et al 2002, Milligan et al 2016). This suggests that grazing removal may have a beneficial effect on wet heathland biodiversity.

Burning

Evidence of burning impacts (managed burns and wildfire) on upland wet heathland is limited to a few studies of heather on peat soils in England and Northern Ireland, which may have limited relevance to the more species-rich wet heathland found in much of Scotland.

For controlled management burns, vegetation biomass increases post-burn to a maximum after 25 years, while heather growth rate peaks at 10 years post-burn (Alday et al 2015). Modelling of carbon stock accumulation over the whole burning cycle shows that above-ground carbon stocks increase with increasing intervals between burns, to a maximum with a 50-year burning interval (Allen et al 2013). In Northern Ireland, burning was found to decrease dissolved carbon losses from the soil, but to increase losses of particulate carbon in water (Worrall et al 2011, Evans et al 2017). However, the net effect on soil carbon stock is not clear.

There is a small amount of evidence for the above-ground effects of wildfire on wet heathland. A study in an English heather-blaeberry heath on wet peaty soil (Clay et al 2011) suggested that wildfire consumed a greater proportion of the above-ground carbon stock than management burns, with 86% of the above-ground carbon stock being lost. Production of charcoal, a very stable form of carbon, may partly mitigate the impact of wildfire on carbon stocks. There is some evidence from a modelling study that carbon losses during wildfire are influenced by management burning regimes; overall carbon losses from wildfire may be less in heathlands managed by short rotation burning, but this depends on the frequency of wildfire (Allen et al 2013).

Evidence for the effects of burning on biodiversity in wet heathland is very limited. A study from northern England suggests that plant diversity was greater in a short (10 year) burning rotation than in a long-term rotation or in unburnt heathland (Milligan et al 2018).

Nitrogen deposition

Evidence for nitrogen deposition effects on carbon stocks in wet heathland is very limited. Laboratory studies of the typical wet heath species heather, cross-leaved heath and *Molinia*, show that nitrogen addition increases biomass in all species, but particularly for *Molinia* (Aerts et al 1991). This suggests nitrogen deposition may increase above-ground carbon stock in wet heath but may also have undesirable effects on plant biodiversity. Nitrogen deposition has also been seen to reduce butterfly diversity in Dutch lowland wet heath (Feest et al 2014).

Climate and GHG changes

No evidence was found for the impacts of increased atmospheric carbon dioxide on carbon stocks or biodiversity in upland wet heath.

Change in rainfall and temperature

No evidence was found for the impacts of drought or warming on carbon stocks or biodiversity in upland wet heath.

7.2.2 What we do not know

Information on the variability in carbon stocks both above and below-ground in Scottish wet heathlands is limited. Data is needed on the spatial variability of carbon stocks in this habitat in relation to environmental gradients (temperature, rainfall, nitrogen deposition) and management impacts.

There is no information on the impacts of drought, warming or increasing atmospheric carbon dioxide on carbon sequestration or the stability of the soil carbon store in wet heathland. Experimental studies would be required to address this knowledge gap.

There is no information on how biodiversity in Scottish wet heathland is related to above and below-ground carbon stocks, particularly for species groups other than plants, including all aspects of grazing and burning.

7.3 Grasslands

7.3.1 What we know

Grazing

A study in a Scottish *Molinia* grassland (Smith et al 2014) showed that *Molinia* tussocks are a very dense store of carbon. In this study, grazing by sheep reduced the abundance of *Molinia* tussocks and thus reduced above-ground carbon stocks, with a 50% reduction in carbon under commercial stocking rates, compared with no grazing. Modelling of the impacts of grazing on soil carbon stocks predicted declining stocks under the commercial stocking rate, and increasing stocks under a low, or no, grazing scenario.

In a study of mat-grass grasslands in England long-term (7 year) removal of sheep grazing resulted in increased above-ground and litter biomass (Medina-Roldan et al 2012). There was no evidence of change in soil carbon stock over this period, but the study was probably too short for there to be a measurable change in soil carbon.

Evidence from studies in Scottish *Molinia* grasslands suggests variable effects of grazing on the diversity of plants and animals. Sheep and cattle grazing promotes higher densities of meadow pipits and beetles, but reduced numbers of insects, spiders, moths and small mammals (Evans et al 2015, Littlewood 2008, Pozsgai et al 2020). Increased cattle grazing on *Molinia* has been found to increase plant diversity (Grant et al 1996). Reduction in grazing intensity to promote carbon storage in *Molinia* grassland may thus have varying impacts on biodiversity across different species groups.

In English and Welsh upland mat-grass grasslands, long-term grazing removal (7-60 years) has been found to result in increased shrub cover and decreased grass cover, but generally had no effect on plant diversity (Hill et al 1992, Medina-Roldan et al 2012, Alday et al 2020). The long-lived nature of many upland plant species means that changes in species richness resulting from altered grazing regimes may take many years to appear.

Burning

No evidence was found for the impacts of burning on carbon stocks above or below-ground, or on biodiversity in *Molinia* grassland.

Nitrogen deposition

There was no evidence on the effects of nitrogen deposition on carbon stocks in upland *Molinia* grasslands in the UK. However, a study of nitrogen deposition effects on a wide range of grasslands across Europe and North America suggests that above-ground biomass typically increases in response to nitrogen deposition (De Schrijver et al 2011). In mown *Molinia* grasslands in Europe, increased nitrogen increased above-ground biomass, but reduced biodiversity (Kotas et al 2017).

In upland acid grasslands in England, there was no evidence for the effects of nitrogen deposition on carbon stocks or biomass but increasing nitrogen deposition was associated with negative effects on moss and plant biodiversity (Lee & Caporn 1998, Carroll et al 2003).

There is good evidence for the impacts of nitrogen deposition on alpine moss-sedge grasslands in Scotland. Nitrogen deposition is associated with both increased carbon sequestration in moss growth and increased carbon loss through decomposition, with a net effect of reduced (by 90%) above-ground carbon storage (Armitage et al 2012, Britton et al 2018). Soil carbon stocks were not altered by nitrogen deposition (Britton et al 2018). Loss of the above-ground carbon stock was associated with reduction in habitat condition and biodiversity value (Britton et al 2018).

Changes in GHGs

No evidence was found for the impacts of increased atmospheric carbon dioxide concentration on carbon stocks above or below-ground or on biodiversity in *Molinia* grassland.

Drought and temperature

No evidence was found on the impacts of drought or warming on carbon stocks or biodiversity in *Molinia* grassland.

A single laboratory study that investigated the effects of short-term drought on carbon fluxes in mat-grass grassland showed that drought reduced carbon uptake by plants, but also reduced carbon losses in soil water; longer term effects of drought remain uncertain however (Johnson et al 2011).

7.3.2 What we do not know

Interpretation of the effects of grazing on carbon stocks in upland *Molinia* grassland is based on a single Scottish study. There is a lack of data with which to determine the variability of carbon stocks in this habitat across Scotland. There is also insufficient data to establish the impact of grazing by sheep, cattle or wild herbivores, at a range of stocking densities, in terms of either direct biomass removal or trampling impacts. Likewise, there is no information on how grazing management for carbon stocks might impact biodiversity in these grasslands.

We found no data on the impacts of burning regimes on carbon stocks above or below-ground in *Molinia* grasslands. Studies are required which assess above and below-ground carbon stocks in relation to burning frequency, particularly in the west of Scotland where this type of grassland is widespread. Information is also required on how biodiversity in *Molinia* grassland interacts with burning and carbon stocks.

There was no information on the response of above or below-ground carbon stocks to nitrogen deposition in the unmanaged or extensively managed *Molinia* grasslands found in Scotland. This information is also lacking for other Scottish upland grassland types. Similarly, we have no information on how any changes in carbon stocks associated with nitrogen deposition might impact biodiversity.

There is a particularly large knowledge gap around the impacts of climate change (drought, temperature increases) and increased atmospheric carbon dioxide on carbon stocks and biodiversity in upland grasslands. Studies are needed at sites across Scotland because variability in the climate baseline is likely to influence responses to drought and warming.

7.4 Interactions

7.4.1 Driver interactions

For clarity, the effects of environmental change and management have been presented here as the individual effects of each driver. However, it is important to note that ecosystems are not subjected to any single driver of change in isolation, but to many drivers of change simultaneously. The effects of environmental change and management drivers will interact, and this may change the outcomes for carbon sequestration and stability of ecosystem carbon stocks. For example, in dry heathland, nitrogen deposition generally has a positive effect on carbon sequestration into biomass. However, exposure to nitrogen deposition can make heather more susceptible to drought, increasing the severity of negative impacts on heather growth (Southon et al 2012). Likewise, nitrogen deposition and grazing can interact, with the effects of grazing removal on carbon stocks being greatest in areas that are also subject to high nitrogen deposition (Smith et al 2015). Many scientific studies focus on a single driver of change; there are a limited number of studies which consider multiple, interacting drivers. This is an important knowledge gap.

7.4.2 Habitat transitions

In addition to their effects within a given habitat type, some of the drivers considered in this review may cause such extreme changes in vegetation structure and plant diversity that the habitat undergoes a transition to another type. Grazing and nitrogen deposition are two examples where a high level of impact can result in transitions from dry or wet heathland to grassland. Conversely, absence of grazing or burning management in upland heathlands may, over time, result in scrub encroachment and a transition from heathland to woodland. Such transitions substantially change the character of the habitat and may have significant implications for carbon cycling processes, carbon stocks and sequestration.

What we know

There is good evidence from studies in Scotland and northern England that carbon sequestration and carbon stock (vegetation plus top 15 cm of soil) is reduced when dry upland heathland undergoes a transition to grassland because of heavy grazing or inappropriate burning management (Quin et al 2014, 2015). Above-ground carbon stocks tend to be greater in grasslands than in heathlands if *Molinia* is the dominant grass, but soil carbon stock and the total ecosystem carbon stock is greater in heathland (Quin et al 2015). Measurement and modelling of carbon dioxide fluxes suggests that upland heathland dominated by heather sequesters twice as much carbon annually as heathland which has degraded to grassland (Quin et al 2014). Restoration of degraded grass-heath back to heather-dominated heathland generally increases carbon stocks. However, the carbon benefit varies between sites and may be small or negative at sites with dense *Molinia* grassland, due to the large carbon stocks in *Molinia* tussocks (Quin et al 2015, Smith et al 2014). There is also good evidence that restoration of degraded grass-dominated heathland typically provides a biodiversity benefit (Littlewood et al 2006 a,b).

Encroachment of trees into dry heathland habitats may occur due to removal of grazing and burning management, or as a direct result of tree planting. There is some evidence from Scotland that planting (without ground preparation) of birch or pine woodland on dry heathland does not always result in increased total ecosystem carbon stock over the first 40 years post-planting. In this case the growth of trees increased the above-ground carbon stock, but there was a reduction in soil carbon stock in the organic horizon, resulting in either no net change in total carbon stock or sometimes a reduction (Friggens et al 2020). Similar findings are reported from analogous habitats across a natural heathland-to-woodland transition in Scandinavia, where soil carbon stores in crowberry-dominated heathland were three times greater than in adjacent birch woodland (Parker et al 2015). Measurement of carbon dioxide fluxes from soil and decomposition of plant litter suggest that soil microbial communities associated with the trees drives the differences in soil carbon (Parker et al 2018, Friggens et al 2020). Resampling of a range of moorland soils, which had been subsequently converted to commercial forestry between 21 and 57 years previously, showed an increase in total soil organic stocks. However, this increase was mainly due to increased thickness of a loose, surface litter layer, comprising relatively undecomposed pine needles and leaves (Lilly et al, 2016).

What we do not know

Evidence for the impact of habitat transitions on carbon storage in upland heathlands and grasslands is limited to relatively few studies, although the evidence base does include sites in Scotland. Some additional evidence for the long-term impact of major habitat type transitions on soil carbon stocks could be gained from comparison of national soil inventory data for different broad habitat types (woodland, heathland, grassland). However, this has the difficulty that the land management history is unknown. While other drivers such as changes in temperature or precipitation can be estimated from climate data, only the impact of major land use changes such as afforestation can be quantified. More data is required to determine differences in above and below-ground carbon stocks between habitats at a local scale and in response to land management. In terms of understanding how to maximise carbon sequestration in the uplands, a particularly important knowledge gap is around the timescales for change in carbon stocks when habitat transitions occur.

8 Concluding remarks

Upland dry heath, wet heath and upland grassland habitats in Scotland are each found on a diversity of soil types. Carbon stocks per unit area and the depth of organic surface soil in Scotland's open upland habitats have been derived from national soil inventory data. However, the resolution of the available spatial data does not allow us to quantify total stocks in each of the individual habitats.

The evidence review found very limited information regarding impacts of land cover and management on soil carbon stocks or GHG emissions; studies giving a full balance sheet of ecosystem stocks and flows of carbon in response to environmental or management change were particularly scarce.

Measured soil carbon stocks from the national inventory provide evidence of a lack of overall change in these habitats in the 25 years prior to 2007. However, these results reflect the interaction of the global drivers of change, such as changing climate and changes in deposition. There are not enough data to extract the impacts of specific management practices on soil carbon stocks in these habitats.

The review of targeted surveys and experimental data showed evidence of impacts of grazing on vegetation carbon stocks in *Molinia* grassland and upland dry heath. However, there was limited evidence on changes in soil carbon stocks.

The review provided some evidence of the impacts of management burns and wildfires on vegetation carbon stocks on upland dry heaths but the data were limited regarding the impact on profile soil carbon.

Evidence on soil and vegetation carbon stocks and biodiversity in upland wet heaths is extremely limited. Few consistent responses were observed and there have been no studies in Scotland.

There is also a lack of data on the interaction of, for example, nitrogen deposition or climate change with management; most studies assess the impact of single drivers.

The dominant greenhouse gasses from open upland habitats have been identified and compared to more intensively managed lowland habitats. However, there is a lack of measured data on full greenhouse gas balances under global and management pressures.

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10 Appendix

10.1 Habitat extents

Table 4: Habitat definitions and key species

Habitat	BAP Habitat	EUNIS Habitat
Upland dry heath	Upland heathland	F4.21 Submontane *Vaccinium* - *Calluna* heaths F4.22 Sub-Atlantic *Calluna* - *Genista* heaths F4.25 Boreo-Atlantic *Erica cinerea* heaths F2.25 Boreo-alpine and arctic heaths
Upland wet heath	Upland heathland	F4.11 Northern wet heaths
***Molinia* grassland**		F4.13 *Molinia caerulea* wet heaths
Other grassland	Acid grassland Acid grassland Acid grassland Acid grassland Acid grassland Montane habitats Acid grassland/Montane habitats Bracken	E1.71 *Nardus stricta* swards E1.72# Species-rich *Nardus* grassland, on siliceous substrates in mountain areas E1.72x Other *Agrostis-Festuca* grassland E1.73 *Deschampsia flexuosa* grassland E3.52 Heath *Juncus* meadows and humid *Nardus stricta* swards E4.32 Oroboreal acidocline grassland E4.32€ Siliceous alpine and boreal grassland E5.31 Sub-Atlantic *Pteridium aquilinum*

Based on https://www.nature.scot/naturescot-commissioned-report-766-manual-terrestrial-eunis-habitats-scotlandTable 5: EUNIS habitat areas (EUNIS Land cover MAP Scotland)

Habitat	EUNIS CODE	EUNIS description	Area [km2]
Blanket Bog	D1	Raised and Blanket bog	9720
Dry Heath	F2	Arctic, alpine, subalpine and extensive scrub	7
	F4.2	Dry heaths	3013
Wet Heath	F4.1	Wet heaths	4188
Wet & Dry Heath	F4	Temperate shrub heathland (Undifferentiated)	12732
Other Grassland Types	E	Grasslands and lands dominated by forbs (herbaceous flowering plants) mosses or lichens	3651
	E4	Alpine, subalpine and extensive grasslands	1289
	E4.3	Acid alpine, subalpine and extensive grassland	2992
	E5	Woodland fringes and clearings and tall forb stands	414
	E5.3	Pteridium aquilinum (Bracken) fields	223
Montane	K	Montane habitats	2870

10.2 Review methods

A Rapid Evidence Assessment systematically reviews both the peer reviewed and grey literature on a topic. The search terms used to screen the peer reviewed literature in Web of

Science Core Collections (http://wok.mimas.ac.uk) combined habitats terms with management or management impact:

- heath OR moorland OR *molinia* OR *calluna* AND
- carbon OR flux OR methane OR nitrous oxide OR greenhouse OR respiration OR decomposition OR organic OR organo OR rhizosphere OR sequestration OR biomass OR CO2 OR GHG OR Deer

Web of Science search returned 2062 papers.

These were then screened by their title and abstract and:

- 1545 were from other disciplines and not relevant for this review.
- 95 papers were excluded as they were studies from outside Europe.
- 98 papers were focused on GHG emissions
- 183 papers were focussed on habitat condition and vegetation carbon stocks
- 18 papers were focussed on land management
- 123 papers were focussed on Soil Carbon

Of these papers the full text of 177 papers were reviewed:

- 16/98 of the GHG emission papers were reviewed
- 102/183 of the habitat condition and C stocks were reviewed
- 12/18 of the land management papers were reviewed
- 47/123 papers on soil carbon were reviewed.

Of these papers 60 are sited in the report as being directly relevant to the questions asked.

An additional 6 papers (Usher et al., 1988, Pozgai et al 2020, Hauson & Coulson.1998, Gardner & Usher., 1998, Feest et al., 2014, Davies & Legg., 2008) that assessed the impacts of pressures on specific aspects of biodiversity (Beetles, Moths and Butterflies, Lichen and other insects) were included. These were followed up from more recent references or known by the project team to outline specific aspects that the initial search hadn't returned.

Of papers co-authored by members of the project team 5 had not come up in the search and were therefore added to the peer reviewed papers that were reviewed (Litlewood et al 2006a&b, 2008, Phoenix et al 2012, Hulme et al 2002).

A further 9 papers were included for further clarification of factors identified in the main search:

- Curtis et al., 2005 and Bobbink et al., 2010 on impacts of N deposition
- Maltby et al., 1996 and Kayll, 2966 providing specific examples of burning in the UK
- Hill et al., 1992, and Milligan et al.,2016, analysing the impacts of grazing in specific locations in the UK
- Harpenslagger et al., 2015 to the processes by which carbon cycling is changed by vegetation and its impact on GHG emissions.
- Poulton et al., 2018 and Minsay et al., 2018 on the principles of soil carbon change

In the papers related to the National Soil Inventory of England and Wales (Bellamy et al 2005 and response by Smith et al 2009) had not come up in the Web of Science search as they covered multiple habitats. However, they specifically addressed soil carbon stock change in the habitats of interest and so it was added to the papers that were reviewed. In addition, a book chapter written by the authors (Baggaley et al 2016) was used as a reference for carbon stocks in Scottish Soils.

The data behind the National Soil Inventory of Scotland was analysed to calculate average and ranges for soil carbon stocks in soils in each of the habitats considered and nationally available land use data was analysed for its ability to define the areas of each of the habitats.

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