These appendices are in support of the report:
Sustaining Ecosystems - English Grouse Moors. April 2022[a].

Appendix 1 - Clean Air[b]

Reducing polluting gas emissions

Upsides

i. Emissions of air pollutants from wildfire have been calculated as substantially degrading air quality with wildfire $PM_{2.5}$ (particulate matter of 2.5 microns) concentrations linked to health problems[1].

ii. Surface concentrations of $PM_{2.5}$ from the Saddleworth Moor wildfire were 4–5.5 times higher than recent seasonal averages and increased by more than 300% locally and by 50% in areas up to 80 km away. The estimated impact of $PM_{2.5}$ mortality due to that fire was £21.1 m[2].

iii. The estimated average aircraft-measured Emission Factor (PM_1) from wildfires is more than twice that of controlled fires and where controlled burning reduces the prevalence of wildfires there may be a net benefit by reducing overall PM emissions[3]. Unlike managed fire, wildfires pose a particularly high risk of particulate matter emissions and the release of 'stored' pollutants. Emissions, particularly of $PM_{2.5}$, are likely to change over the course of a wildfire due to the change in fuel source from surface vegetation (with emission estimates ranging from 6.3–15.3 g/kg for vegetation types burned) to the underlying peat (with higher emissions per unit burnt - estimated range from 6–30 g/kg) (emissions estimates from Global Fire Emissions Database v4[2]).

iv. The nature of peatland wildfires (well-oxygenated, high emissions and dense ground level smoke) means that their impacts on air pollution may differ from other wildfire types[2].

v. Methane releases from natural sources such as wildfires and wetlands are projected to increase, thereby affecting air quality through increasing ozone concentrations. Recent research has demonstrated how methane removal can not only mitigate against global climate change but also improve air quality[4].

Downsides

vi. The incomplete burning of vegetation generates particulate matter and polycyclic aromatic hydrocarbons (PAHs)[5,6] with unit area emissions possibly around half of those from wildfire (see above).

[a] https://www.gwct.org.uk/englishgrousemoors
[b] Greenhouse gas emissions are considered under Appendix 5 – Mitigating and adapting to climate change

vii. Agricultural machinery used for cutting that are not Euro-6 compliant are likely to be a contributor to air pollutant emissions; however, the extent of this is not quantified.

Challenges

viii. Public policy constraint on heather burning (most recently the Heather and Grass etc. Burning (England) Regulations 2021[7]) is likely to increase unburnt vegetative fuel load (i.e. heather, grass and scrub biomass), which may increase the risk and severity of wildfire[8] and, consequently, the amount of PM emissions.

ix. Wildfire events are often linked to human recreation with access rates being a proxy for availability of ignition sources – climate change may increase this risk due to increasing visitor numbers[9]. The Met Office's Fire Severity Index[10] indicates when wildfire risk is high enough to require the closure of open-access land.

x. Degraded peatlands, and peatlands during a drought, are a particular wildfire risk[11,12].

Removing air pollutants

Upsides

xi. The ONS estimated the annual valuation of pollution removal for Mountains, Moorlands and Heaths (MMH) at £10.9 million in 2017, on the basis of avoided healthcare costs[13]. The UK's MMH covers 3,664,200 hectares and so this equates to £2.97/ha. Using this value we estimate that the 423,000 hectares under English grouse moor management removes £1.26m of pollutants annually.

xii. Traits associated with heather moorland and peatlands vegetation enhance PM capture notably surface roughness, leaf surface morphology and multi-species habitats[14].

Downsides

xiii. Open canopy woodland has been shown to be an effective pollution trap[15] but comparative research has not been undertaken on peatlands and heather moorlands.

xiv. The ONS estimated that removal of air pollution by UK woodland equated to an annual saving of £938.0 million in health costs in 2017[16]. This equates to approximately £293/ha or c100 times that of MMH.

xv. The removal of air pollutants by vegetation impacts habitat quality through acidification and nitrogen enrichment, encouraging vegetation changes away from the specialist peatland species[17].

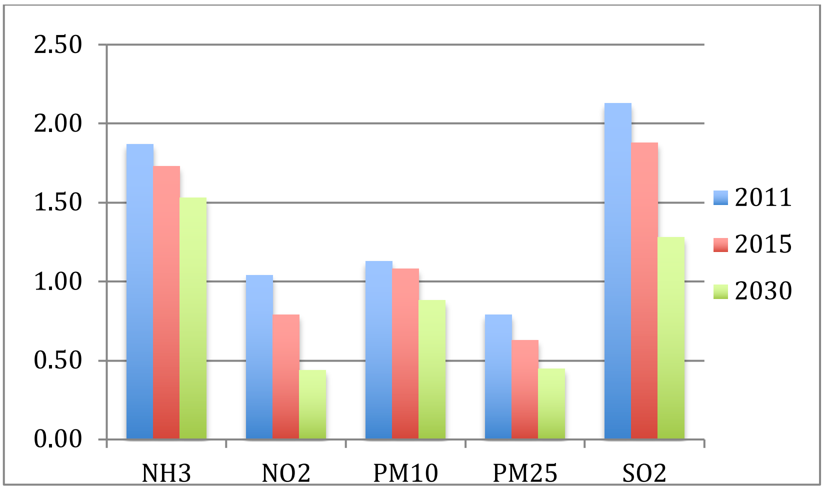
Challenges

xvi. In recent years the deposition of atmospheric sulphur is likely to have fallen below the 'critical load' likely to threaten peat bogs in good condition, but the damage done to peatlands in the South Pennines in particular is only slowly being reversed[18].

xvii. The impacts of pollution reduction and removal on habitat quality and other environmental goods and services are complex and have been summarised at http://www.apis.ac.uk/ecosystem-services-and-air-pollution-impacts and in IUCN briefing paper 13 (2016)[18].

xviii. Air pollution emissions have fallen and so the value of this service will continue to decline. The ONS[13] notes that this is largely based on reductions in ozone emissions with PM2.5 representing the lowest proportion of all pollution removal included in the ONS analysis.

Figure 1: UK emissions (thousands of tonnes) in 2011, 2015 and 2030 forecast.[13]



Appendix 2 – Clean and plentiful water

Upsides

i. The blocking of drainage ditches by grouse moor owners and managers is likely to be improving water quality by preventing the further release of sulphur, nitrate, ammonia and metals that had occurred due to the lowering of water tables associated with peat erosion or drainage[19].

ii. Water from functioning peatlands is high quality because vegetation, especially mosses and lichens, captures and retains a range of atmospheric pollutants[17]. The ONS estimates the annual value of UK drinking water from peatlands at £888 million and the asset value at £18,366 million in 2016[20]. These ONS estimates are based on the costs relating to both water supply and water treatment.

iii. By dividing these figures by the area of peatland in the UK (estimated by ONS as 2,962,622 hectares) and then multiplying by the area of English peatlands under grouse moor management (282,000 hectares[8]), we estimate that the annual value of English GMM to drinking water provision is c.£84.5 million and asset value c.£1750 million.

iv. Vegetation cover represents a key control on storm runoff in peatland catchments[21], and therefore the quantity and quality of the water downstream.

Downsides

v. Degraded peatlands comprise areas of exposed bare peat, which can adversely affect the quality of drinking water through increases in dissolved organic carbon, which causes brown peaty water[22], acidity and concentrations of suspended sediments or fine particulate organic matter and metals[19].

vi. Concerns have been expressed that disease control on grouse moors (notably flubendazole in medicated grit) could impact on water quality. Review work in Scotland suggested that while the risk was low, concentrations may be underestimated where there is poor practice and that uncertainties required further investigation[23].

Challenges

vii. Restoring degraded peatland through re-vegetation and grip blocking may affect the regulation of water supply. Rewetting and saturation with water is likely to lead peatlands to produce 'flashy' run-off[17] reduced water quality[24] through increased over-land flow. See also Flood mitigation (Appendix 4 - Reducing risk of harm from environmental hazards).

viii. The IUCN[25] has noted that further research is required on the impact of climate change on water quality. However an increase in 'intense' rainfall events[26] and changes in snow-lie are likely to influence water quality[17] (notably particulate carbon losses via runoff) while drought and rewetting sequences increasing Dissolved Organic Carbon (DOC) losses[27]. Rainfall is likely to be more important than temperature in shaping long-term changes in runoff[28].

ix. Peatland instability due to climatic and land management changes raises the risk of release of some heavy metals and Persistent Organic Compounds into river systems[17] thereby affecting water quality.

x. Vegetative change in peatlands may occur due to climate change, land management and nitrogen deposition[29] and this can affect DOC losses[30].

Opportunity

xi. The impacts that controlled burning (and interactions with drainage and grazing) may have on water quality are still not well understood. Study results differ depending on timescale since burning event and spatial scale. Commonly cited studies of burning and water colour have highly divergent views[31–33].

Appendix 3 - Thriving plants and wildlife

Upsides

i. Designations reflected the biodiversity importance of managed moorlands in England at the time of designation.

ii. There are four upland SPAs covering an area of c.230,000ha. 74% of the area of upland SPAs is managed as grouse moors. The four upland SPAs with >90% of their area at or above 200m are (and the qualifying species covered by the designation):

   a. North Pennine Moors – Hen Harrier, Merlin, Peregrine Falcon and Golden Plover
   b. North York Moors – Merlin and Golden Plover
   c. South Pennine Moors – Short-eared Owl, Merlin and Golden Plover, and
   d. Bowland Fells – Hen Harrier, Merlin, Lesser Black-backed Gull.

iii. Between 1994 and 2019 the English moorland bird index has increased by 13%[34]. This index tracks the abundance of Red Grouse, Golden Plover, Curlew, Common Gull, Meadow Pipit, Whinchat, Wheatear, Raven, Black Grouse, Hen Harrier, Golden Eagle and Merlin.

iv. Best practice legal grouse moor management can support the six SPA bird indicator species listed above:

   a. Hen Harrier - Clutch survival and productivity was higher on a keepered moor with predation by foxes being the main cause of breeding failure[35]. Natural England has reported that 2021 was the best breeding year in England since the 1960s, with 84 chicks fledged from nests across uplands in County Durham, Cumbria, Lancashire, Northumberland and Yorkshire[36].
   b. Merlin – The species benefits from predator management carried out on grouse moors[37] and shows peak occurrence at intermediate levels of controlled burning[38].
   c. Lesser Black-backed Gull (migratory) - Nesting is more common where ground predation risk is low[39].
   d. Peregrine Falcon – Grouse moors provide suitable breeding habitat and an abundant food supply[40].
   e. Short-eared Owl – A mosaic of heather ages is thought to support populations given their diet of small mammals, especially voles[41].
   f. Golden Plover – Breeding densities of golden plover are highest where GMM is carried out[42,43].

v. GMM is the preferred habitat for the amber-listed red grouse, and also provides refuges for other birds. Lapwings are positively associated with moorland managed for grouse shooting[43]. Curlew are red-listed and one of the UK's most pressing bird conservation priorities following habitat loss (to farmland and woodland) and increased predation[44]. GMM supports Curlew breeding populations whose prevalence is related to percentage of controlled burning[42] and breeding success and numbers improved where predators were controlled[43]. Twite[45] and Lesser Redpoll[42] are associated with hill edge (including nesting on heather moorland) and burning extent respectively. In England Black grouse are largely confined to the North Pennines. 90% of the English population is estimated to exist on moorland keepered for red grouse, benefitting from reduced predation pressure and beneficial grazing restrictions[46].

vi. The success of the hen harrier brood management trial indicates how GMM can integrate with social-legal objectives when public policy is supportive. See figure 4.1.3.1 in main report[c].

vii. There is a remnant mountain hare population in the Peak District. Mountain hares benefit from GMM which enhances habitat quality and reduces predation pressure[47].

viii. A unique assemblage of invertebrates, some important to carbon cycling, benefit from GMM's objective of variable habitat structure. There are important invertebrate assemblages related to heather and blanket bog peatlands. Habitats characterized by a mosaic of vegetation communities and structures are likely to support the greatest invertebrate diversity and abundance[48]. Rare ground beetles are associated with sites managed by burning and cutting. Some beetle species are found only on unmanaged wet *Calluna* moor with the highest median site rarity scores found on dry, open, managed *Calluna* sites[49]. Invertebrates have been found to be most abundant in the building-phase of cut heather rather than in fresh cut or mature heather[50]. Drain blocking could slow the predicted damaging effects of warmer, drier summers on craneflies[51]. Preventing vegetation succession (through management) could also be important in retaining the particular communities associated with moorlands[52].

ix. Moths and butterflies are good indicators of environmental change; specialist Moorland Moths have increased by 80% between1991 to 2018[34] though there are fluctuations in the index (range c-40 to +80) with 1996, 2003, 2006, 2010 and 2018 being good years.

x. The four upland SACs (Special Areas of Conservation) related to areas managed for GMM cover an area of c.224,000ha.

[c] https://www.gwct.org.uk/englishgrousemoors

Table 1: The conservation status of key habitats on 4 UK Special Areas of Conservation[d]:

	North Atlantic wet heath with *Erica tetralix*	European Dry Heath	Blanket Bog
North Pennines (1998-2015)	Good	Good	Good
North York Moors (2001-2015)	Good	Good	Good
South Pennines (2001-2015)	Average	Average	Average
Border Mires (1996-2015)	Good	Good	Excellent

xi. Managed (or controlled) burning can aid Sphagnum moss establishment by removing the heather, grass or sedge canopy resulting in increased light and reduced competition[53] and that the highest levels of Sphagnum moss and cotton grass were on areas burnt between three and ten years previously[54].

Downsides

xii. The numbers and distribution of hen harriers and peregrine falcons on many upland areas managed under GMM remains worse than would be expected from the available habitat and prey resource, suggesting direct (illegal killing) and indirect (habitat management) actions could be restricting their range and populations, although there has been a rapid change for the better in recent years[55]. The illegal killing of protected birds of prey, including those which have attained favourable conservation status, may be related to evidence that in some circumstances raptor predation has been shown to prevent the economic sustainability of a grouse moor, and consequently the conservation of endangered upland waders[56]. The GWCT condemns illegal crimes against wildlife and is committed to finding an effective and practical resolution to the conflict between red grouse and raptors. Our involvement in the Langholm Moor Demonstration Project was testament to this intent. The outcome of this project reinforces our belief that the best of traditional moorland management can and should be married to new approaches and techniques in order to support more birds of prey, with a sustainable distribution across suitable moorland habitat.

xiii. Native 'clough[e]' woodland is relatively scarce (c.3300ha[f]) and upland semi-natural woods have declined by 30 to 40% over the last 50 to 60 years. Native clough woodlands are typically made up of a mix of species such as Sessile Oak, Birch, Rowan, Aspen, Alder, Willow, Hawthorn and Holly. They are open in nature and have varied structures. Their decline is

[d] see https://sac.jncc.gov.uk/site/

[e] 'Cloughs' or 'cleughs' or gills are the narrow, steeply sided and sloped stream courses that link main river valleys with upland moorlands.

[f] Based on National Forest Inventory mixed mainly broadleaved woodland and low-density woodland for upland areas (at or above 200m)

primarily associated with commercial replanting and grazing preventing regeneration[57].

Challenges

xiv. Heather moorland, a globally important habitat[g], has declined in extent by more than 27% since 1945[58], with c.210,000ha remaining in England (CEH Land Cover data 2019 (see Table 3.1, page 12 in main report[h])). Our research for this report suggests that it continues to decline being replaced by heather grassland (less than 25% heather cover) – see Table 3.1, page 12 of main report) although there is a lack of detailed long-term data on the extent of heather habitats present in the English uplands.

xv. 'Net zero' public policy plays a role in this loss:

- it emphasises reducing heather as part of peatland restoration.
- SSSI condition assessments result in controlled burning being suppressed by explicitly assuming that fire only has damaging effects on peatlands. SSSI condition assessments are based on JNCC guidance or Common Standards Monitoring. For the uplands this guidance was produced in 2009 and states that to be in 'good condition' blanket bog and wet heath habitats should have "*...no observable signs of burning into the moss, liverwort or lichen layer or exposure of peat surface due to burning*" and for Alpine dwarf shrub heath "*There should be no signs of burning inside the feature boundaries.*"[59]. This inflates estimates of the impact of fire by assuming the whole site is affected and also ignores any beneficial effects of fire[60].
- The Heather & Grass etc. Burning (England) Regulations 2021 prevent controlled burning on around 142,000 ha of blanket bog much of which was designated whilst being managed, including burning, as grouse moor.
- Woodland cover, favouring broadleaved/mixed woodland (National Forest Inventory) has increased in the uplands from 9.9% to 11.6% between 1990 and 2015 according to UK CEH Land Cover Map data. Public policy, private green finance and alternative land use likely to result in further tree stocking on formerly open moorland.

xvi. Warmer temperatures (assuming sufficient soil moisture)[61] are likely to increase biomass production, particularly on heathlands, resulting in a need to maintain open habitats through active management[17]. These effects will be multiplied where livestock numbers decline following changes in agricultural support regimes and rewilding management – with consequent impacts on biodiversity and favourable condition.

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[g] The 1992 Rio Convention on Biodiversity recognised the global importance of UK heather moorland

[h] https://www.gwct.org.uk/englishgrousemoors

xvii. The damaging loss of GMM for upland birds species has been documented in SW Scotland[62]. In the Berwyn Mountains in Wales, where grouse shooting has ceased, lapwing are extinct, golden plover are down to one pair, and curlew have declined by 90%[63].

xviii. GMM can mitigate but not fully compensate for biodiversity losses across the whole of England - nationally, numbers of Whinchat and Merlin have halved (1994-2017), and Curlew numbers across all suitable habitats have been in decline since around 1970 falling 14% between 2005 and 2015 alone[64]. It has not been possible to identify trends for these species on just GMM areas but for Merlin regional population declines were not limited to areas dominated by grouse moors[65].

Opportunities

xix. GMM should seek to support clough woodlands. Natural England should assist with this by supporting grouse moors in their use of controlled burning, grazing and predator control to protect the woodland and ground nesting moorland species.

xx. Legally controllable predators, such as foxes and crows, are taken on grouse moors to protect nesting grouse and their chicks. This reduced predation pressure has benefits for many other ground-nesting birds including threatened waders such as curlew and golden plover[43]. Predator control techniques are now well regulated and have become more target specific, effective and humane. In some habitats it appears that there is little impact of predator removal on predator populations due to replacement/immigration[66].

xxi. Drier summers mean rewetting some peatland (balanced against methane emissions and the need to allow some buffer for water storage) could benefit invertebrate abundance and consequently bird populations such as Golden Plover[51].

xxii. As elsewhere, data inconsistencies (definitions, monitoring protocols) and lack of ground-truthing make it difficult to determine precise details of habitat change and species diversity. Grouse moor managers should take more responsibility for collecting and sharing field data that provides evidence of their best practice (see section 6 of main report[i])[67].

xxiii. The definition of favourable condition may need to be different in the future if soil, habitat and species capabilities in relation to climatic conditions have been irretrievably affected by anthropogenic action including climate change[68]. The determination of favourable condition focuses on the presence of key indicator plant species as these are a factor in ecosystem functioning. However research in France[69] showed

[i] https://www.gwct.org.uk/englishgrousemoors

that the forecast increased frequency of droughts and consequent lowering of water tables could affect *Sphagnum* function. That said it appears that peatlands can adapt to climate change with different plant communities that maintain peat bog function because the new species are functionally identical[70].

xxiv. GMM provides an economic incentive for the conservation of upland ecosystems. Policy should capitalise on this to encourage the creation of 'Moorland *Clusters*[j]' such as the Peak District Nature Improvement Area (NIA).

[j] Farmer Clusters are groups of farmers working together, voluntarily to improve nature conservation and the environment on their farms. They are farmer-led, bottom-up and supported by retained environmental advisors (often, but not always, funded through the Countryside Stewardship Facilitation Fund).

Appendix 4 - Reducing risk of harm from environmental hazards

4.1 Reducing flood risk

Upsides

i. Research suggests that surface roughness which is enhanced by maintaining or restoring the 'hummock and pool' micro-topography and re-vegetating bare peat surfaces is key to 'slowing the flow' and improving 'within-event' water storage[21,71]. Drain/grip blocking may also reduce overland flows but outcomes are highly site-specific and related to the orientation of the drain/grip[21]. Avoiding bare peat and blocking drains are now common management actions on grouse moors which extend to c423,000 hectares across England's uplands.

Downsides

ii. Modelled data suggests that over short time scales and small areas controlled burning may allow easier surface flow[72]. However there is no consistent empirical evidence for the impacts of controlled burning on surface micro-topography and the two studies that suggested controlled burning led to an increase in overland flow have been criticised for methodological flaws[73].

iii. Overgrazing has been shown to reduce flood management capability[72] so sheep stocking levels for GMM must be appropriate for burning intensity, rate of habitat regeneration and local likelihood of severe weather events.

Challenges

iv. To date it has not been possible to supply a total 'value' for the protection and mitigation of flooding from upland peatlands because of the uncertainty of the contribution that peatland, wetted or unwetted, makes to natural flood management (NFM)[20].

v. Short term or limited site data shows peat can store large quantities of water (c85-95% of its volume) leading to the misconception that peatlands definitely a beneficial role in NFM when intact peatlands actually have minimal additional capacity to absorb water as water-tables are already close to the surface[21,74]. No study has fully established a causal link between peatland vegetation management and flooding downstream because defining how much controlled burning, cutting, or grazing is too much in a particular area is difficult given the complexity of factors at the catchment scale[73].

vi. Once peatland soils and surface vegetation are saturated there is a risk of over-land flow causing downstream flooding[24] suggesting that full rewetting may not always be appropriate in flood-prone catchments given projected increases in rainfall intensity with climate change.

vii. Run-off (and therefore downstream flood risk) may be affected by managing the vegetation by mowing/cutting as it affects the plot micro-topography by removing the tops of hummocks and leveling the peat surface and therefore reducing water retention at least for periods immediately after cutting[30].

Opportunities

viii. Water table levels are affected by evapo-transpiration and changes in surface cover and vegetation alter soil water storage and the prevalence of overland flow generation within storm events[75]. Research in lowland situations identifies water table as the over-riding control on GHG emissions[76]. Research is needed to determine the height of water table in upland peatland and associated management approaches that best balance a) climate mitigation objectives with b) flooding and c) biodiversity ambitions.

ix. Some studies suggest that NFM via peatland restoration is applicable to small (<20 km^2) catchments but the evidence at larger catchments is from modeling only with inconsistent evidence across restoration approaches[21].

x. Research[21] suggests that peatlands subject to intensive and extensive wildfires have ‘flashier’ responses to rainfall events due to wildfires removing surface vegetation, therefore reducing surface roughness, and creating smooth, hard peat ‘crust’ surfaces.

4.2 Reducing wildfire

Upsides

i. Wildfire threat can be mitigated by reducing fuel load (mainly determined by the volume of vegetation) through controlled burning, particularly on peat dominated upland heath, the creation of fire breaks (by burning or cutting with brash removal[77]), and perhaps by rewetting (where hydrology and geology permit)[8].

ii. Gamekeepers are involved in many local wildfire groups which bring together a variety of stakeholders to address wildfire risk and issues at local level and support the Fire & Rescue Service (FRS) at wildfires[k]. A proportion of wildfires, including out-of-control managed burns, are brought under control by gamekeepers without the need to involve the FRS.

Downsides

iii. A Natural England Evidence Review[78] on wildfires stated that there is "*Strong evidence …. that, in the minority of cases when a more specific cause was assigned [in the uplands]... (62, only 10% of all upland fires), …. the majority were assigned to land manager burns (68%), followed by campfires (9%) and barbeques (8%)*". Thus, very few wildfires were certainly caused by farming, conservation or GMM. The review went on to state that interpretation of this data requires care given the small number in the sample and the bias and subjectivity in the assignment as to cause as a result of land managers rarely causing wildfires but typically remaining to fight and control them, while the gross majority of wildfires are caused wilfully or unknowingly by persons unknown.

Challenges

iv. Alongside increased land-use and recreational pressures, hotter and drier summers will increase the risk of conditions favourable for the ignition and spread of wildfire[79]. Whilst the chance of a summer as hot as 2018 (when the Saddleworth and Winter Hill wildfires occurred) was low (<10%), by 2050 hot summers could become about 50% more common and by 2080 the combination of higher temperatures, decreased summer rainfall and drier soils could led to a 30%–50% increased risk of wildfire in the UK[80]. Wildfires are episodic, generally occurring in late spring, when the potential fuel consists of dry fine fuels from dead vegetation after winter, and during hot summers[81]. Regularly removing combustible plant material may be particularly important for drier, shallower peats (less than 1m deep), which can be more vulnerable to wildfire damage than deeper peats[82].

[k] e.g https://www.politics.co.uk/opinion-former/press-release/2020/04/27/gamekeepers-praised-for-efforts-fighting-wildfires/

v. Wildfires also occur in upland grasslands and forests (Table 2).

Table 2: Size of wildfire incidents (area burnt) by land cover class in hectares, England, 2009 to 2017

	2009 to 10	2010 to 11	2011 to 12	2012 to 13	2013 to 14	2014 to 15	2015 to 16	2016 to 17
Broadleaved woodland (NFI)	34	123	62	18	66	55	79	23
Semi-natural Grassland	336	884	872	298	658	54	212	656
Mountain, Heath and Bog	202	2,824	11,481	318	654	769	823	538
Total semi-natural	572	3,831	12,415	634	1,378	878	1,114	1,216

Source: ONS/Forest Research

vi. Natural bog is not immune from wildfire during periods of drought due to the reduced moisture content in the surface vegetation and peat (physiological drought) and leaf damage[1,83,84] and once ignited even damp peat can smoulder for a long period[85].

vii. The negative ecological impact of preventing all fire has been noted in America[8] but there has been no detailed research in the UK on the impacts of fire exclusion or the reduction/cessation of other land management[60]. The removal of or reduction in management under some rewilding approaches (such as the impacts of reducing deer[86,87] and sheep numbers) is of concern as this will lead to an increasing vegetative fuel load[88]. It is speculated that reintroducing megafauna can moderate fire regimes by controlling the vegetation and engineering the soil and litter layer[89].

viii. A common approach to restoring peatland is rewetting, usually accompanied by the cessation of vegetation management. Except under rare permanent bog and pool conditions, this will result in a significant increase in above-ground biomass[90] and a higher fuel load over extensive areas with the potential to increase the likelihood of a severe wildfire given current predictions[91]. Rewetted peatland may not prevent the horizontal and downward spread of smouldering peatland wildfires, particularly as they usually occur during the summer when there is reduced moisture content[24,32].

Opportunities

ix. Cutting can be used to create firebreaks but the brash should be removed otherwise it can enhance wildfire risk as well as smothering re-growth[30]. The results of the on-going research by York University will provide data to guide future cutting approaches[92].

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[1] Reported by Scottish Fire & Rescue Service as regards the 2019 Morayshire and Flow Country wildfires.

x. The costs of wildfires are seldom quantified. As events occur more data is being collected but even these may not fully reflect the total cost per wildfire. Some individual estimated costings have been collated for the Saddleworth Moor wildfire in 2018:

- £21.1million cost to economy from health impacts (PM2.5)[2].
- £3.6 million lost through loss of 15,400 tonnes of carbon sequestration capacity[93].
- £1.1-1.6m of carbon emissions (based on estimates of soil carbon losses only (no calculation of carbon from surface biomass was included))[94].
- up to £1m estimated cost to Fire & Rescue Service (FRS) from managing a typical single, large moorland fire[95].
- £205,000 impact on the local economy of fewer tourist visits[93].

xi. The additional 'costs' of the Saddleworth fire (1100ha) in 2018 could be:

a. Surface combustion on near natural bogs could release 18t CO_2/ha in a wildfire alone[96]. During the Saddleworth Moor wildfire this could have equated to another 19,800t CO_2.

b. Legacy emissions from a degraded site. Assuming the Saddleworth Moor site is the equivalent of drained bare peat, which it is estimated emits 13.28tCO_2e/ha/yr[97], this suggests that the Saddleworth Moor wildfire event would lead to in excess of 14,500t CO2e/yr being released, at least initially.

c. Post-wildfire effects will include increased erosion. Exposed peat can be lost by wind-blow, surface water flow and frost heave, resulting in losses of 0.8-1.0cm per year[98].

4.3 Controlling tick-borne disease

Upsides

i. Graziers in many parts of upland UK need to treat sheep with chemical acaricides to reduce tick worry and tick borne diseases[99,100]. Tick biting and tick-borne diseases also have an impact on red grouse survival, breeding success and grouse densities thereby impacting on the potential shooting surplus[101]. Grouse shooting estates monitor tick burdens on shot grouse and test for louping-ill prevalence. Where tick density is high, an acaricide treatment (and when available vaccination) programme on the sheep grazing the moor may be introduced.

ii. Using sheep as a means of controlling tick-borne diseases has been explored as a policy to support upland sustainability[102,103].

iii. Tick populations are found in a wide range of habitats where a moist vegetation layer prevents desiccation and death and vegetation is tall enough to climb up and latch onto a host.

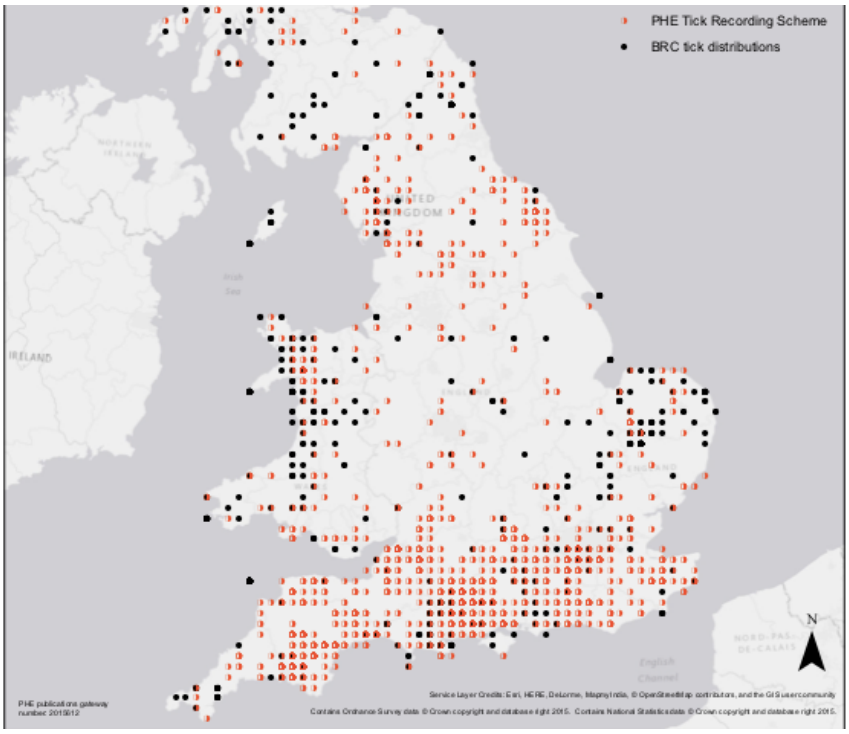

Figure 2: Ticks distribution in England based on Public Health England (PHE) and Biological Records Centre (BRC) data.

Challenges

iv. Public Health England, the Health & Safety Executive and some national park authorities provide advice on the risk to human health of Lyme Disease (LD), a high-profile tick-borne disease. The number of LD cases has increased rapidly with an incidence rate of 12.1 per 100 000 persons per year and an estimated total for the UK of 7738 in 2012; although numbers are probably under-reported[104].

v. The number of tick-borne diseases is increasing dramatically with seven diseases currently posing serious health risks to birds, mammals, and people in the UK. Tick-borne diseases include arborvirus (which includes Tick-Borne Encephalitis and the Flavivirus group); protistans; bacteria (including Lyme Disease); tick paralysis; and alpha gal syndrome[105]. In 2020 Public Health England confirmed the first case of babesiosis and a probable second case of tick-borne encephalitis in England.

vi. Societal costs for LD relate to healthcare costs, but these are not fully understood[106]. No data exists for England but a 2003 analysis estimated a cost of £331,000 per annum in Scotland[107] with case numbers increasing since then[108].

vii. GWCT research[109] has shown that regular treatment of sheep with an acaricide can reduce the prevalence of LIV in red grouse. The annual number of acaricide treatments is higher if managing for red grouse and sheep rather than just for sheep. GWCT estimates £2/adult sheep/yr based on data from its demonstration farm in Aberdeenshire. It is expected that the number of treatments to protect recreational visitors from tick bites and LD would be similar to that for red grouse tick management.

Appendix 5 – Mitigating and adapting to climate change

a) Protecting existing carbon (peat)

Upsides

i. Grouse populations can benefit from improvements to peatland habitat and soil condition. Over the last 25 years grouse moor managers have re-vegetated bare peat and blocked grips (drains) primarily cut for agriculture. Unblocked peat drains can increase peatland carbon losses by 9t CO_2e/ha each year[97]. The Moorland Association calculates that its member's actions have reduced CO2 emissions by 61,126 tonnes per year over the last 10 years.

ii. The impact of wildfires on peatland carbon sequestration and fluxes[110] is of concern given anticipated increases in their occurrence due to climate change. More detail is presented in Appendix 4.2: Reducing the risk of environmental hazards – wildfire mitigation.

iii. Tree planting on organic rich soils will probably not lead to an increase in net carbon sequestration within a native tree ecosystem even several years after planting[111]. The loss of soil carbon cancels out the increase in the tree's biomass carbon over decades. GMM provides a viable economic and biodiversity alternative to tree planting and the retention of heather moorland and blanket bog.

Downsides

iv. Three studies investigated recent burning trends (in area and timing):

- Allen KA *et al* (2016) Prescribed moorland burning meets good practice guidelines: A monitoring case study using aerial photography in the Peak District, UK. *Ecol Indic* 62:76–85. https://doi.org/10.1016/j.ecolind.2015.11.030
- Douglas DJ *et al* (2015) Vegetation burning for game management in the UK uplands is increasing and overlaps spatially with soil carbon and protected areas. *Biol Conserv* 191:243–250
- Thacker J, *et al* (2014). Burning in the English uplands: a review, reconciliation and comparison of results of Natural England's burn monitoring: 2005–2014. Natural England, Peterborough, UK

v. However there are weaknesses in the data that these three studies present: no data was presented for overall burning trends in the last 5-10 years; remote-sensing technology (aerial imagery) was used in all studies but only one used ground-truthing to confirm the data (Allen *et al* (2016)); and, temporal trends and burning rotations were considered in only two of the studies (Allen *et al* (2016) and Thacker *et al* (2014)). A recent study used satellite imagery with finer resolution, more frequent return intervals and broader coverage to determine extent and burn frequency during the period 2015-2020[112]. This found that area managed varied by moorland region and year with the shortest average rotation on the North York Moors (20 years) and the longest the North Pennines (66 years). This study did not compare extent and frequency with earlier periods and we believe there is still no accurate assessment of whether burn area or frequency has changed compared to previous decades.

vi. Methane fluxes increase with rising water tables and warmer temperatures[113]. Wetlands, wildfires and thawing permafrost are projected to be natural sources in the future[4]. Methane makes a significant contribution to net GHG emissions on grouse moors[30] but values are similar to rewetted bogs[114]. Latest emission factors (EF)[97] demonstrate this with a revised EF for rewetted bog of 3.91 (as opposed to 0.81 previously reported in 2017[115]).

Challenges

vii. English grouse moors include 41% of England's peat area[m] but emit only 1 - 5% of total peatland emissions in England, depending on estimates of area, peat condition and level of emissions[8]. This compares very favourably to lowland arable agriculture which covers c.24% of England's peat area and which are the source of 64% of peatland GHG emissions (23.38-28.45t CO2e/ha/yr[97]).

viii. Many, including Natural England[116], recognize that controlled burning can complement peatland restoration and climate change mitigation through reducing emissions, but the available short term data on it is inadequate to accurately assess the current contribution[24] (see also opportunities). This data gap means that the negative narrative around heather burning[60] cannot be addressed, leading to public policy failing to recognize the potential value of vegetation management in minimising fire and erosion threats to upland carbon stores.

ix. The individual effects of controlled burning and drainage on peat function have not been determined and so the two become conflated[60]. Controlled burning has been shown to lower water table depth for up to 10 years in some areas[117]. But drainage has had the most significant effect on peatland hydrology given its spatial extent. Moorland ditching and afforestation have been identified as the two most important factors affecting the hydrology of upland peatland[118]. The peak rate of drainage was estimated to be 100,000 ha/yr in 1970 in response to public grants which supported this activity for the purposes of improving hill farming.

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[m] Based on the Moorland Association figure of 282,000 ha of grouse moor in England on peatland above the moorland line

x. Cutting and leaving the brash has implications for net zero ambitions. Its decomposition releases GHG emissions, possibly 'locking away' less C than via charcoal from burning[119].

Opportunities

xi. The historic and current production of biochar following landscape fires (also called black carbon) is not currently accounted for in UK carbon budgets[119,120] , yet biochar production by controlled fires could be a significant sink for atmospheric CO_2[121,122]. Failing to account for biochar sequestration is probably leading to overestimates of the impact of burning on net C stocks and fluxes in upland soils. Biochar also has the potential to mitigate other GHG emissions (such as methane[123,124]) and aid peatland restoration through its interaction with the soil microbiome[125] and benefits to soil structure and stability[126].

xii. Long-term research studies should be used to inform ecologically driven burning practices. Research assessing carbon accumulation over the last few hundred years on blanket bog sites under rotational grouse moor burn management and found that "*All sites showed considerable net carbon accumulation during active grouse moor management periods*"[119]. Much of this effect may be due to vigorous plant regrowth after burning.

xiii. Over long time scales (>50 years) controlled burning can help transfer carbon captured by photosynthesis to soil microbes, with no net loss of carbon compared to pre-burn levels[127].

xiv. Managed burning rotations could complement peatland restoration as controlled burns may have a role in suppressing methane emissions[110,128]. Dwarf shrub heath may be a better methane modulator than grass[129].

xv. Research is needed to define a functioning 'healthy'[n] peatland in today's climate[118]. Today's peatland may be a completely different type of healthy, functioning peatland from that which formed a millennia ago. For example, bio-climatic envelope models predict that active peat formation will decline in the absence of suitable climatic conditions but these do not account for feedbacks that may act as buffers to change such as climate-peatland SOC (Soil Organic Carbon) feedbacks[130]. In addition recent research has identified a regime shift or tipping point where peat accumulation started to re-occur naturally c100-150 years ago; the reasons for it not being explained solely by climate with local topographic conditions likely to be important in creating suitable hydrological conditions[131].

[n] A healthy ecosystem is defined as one that is sustainable - that is it has the ability to maintain its structure (organization) and function (vigour) over time in the face of external stress (resilience)[143]

b) Storing more (sequestering) carbon

Upsides

xvi. The ONS estimate that mountains, moorlands and heaths sequestered 1.99 MtCO2e in 2017[13] relates entirely to estimated upland grassland emissions. Upland peatlands are thought to emit carbon at an average rate of 3tCO_2e/ha rather than acting as a sink[132]. The contribution of heather and biochar from burning to upland carbon budgets is likely to have been underestimated in previous carbon inventories[133]. However the potential benefit to carbon sequestration of atmospheric nitrogen deposition[134] may be declining as pollution levels fall.

xvii. Research is needed into the factors that influence the amount of biochar produced and its residence time such as weather conditions, fuel loads, feedstocks, fire types[135], fire residence and fire temperature[136] in order to maximize its benefits to carbon sequestration and peatland restoration.

Challenges

xviii. 'No burn management' is being promoted without a good understanding of its implications for ecosystem services such as biodiversity or long-term carbon cycles at a landscape scale[137]. For example, heather and grass cutting is being promoted without adequate assessment of impacts such as mowers flattening the surface and affecting botanical biodiversity[137].

xix. Public media 'framing' of upland vegetation burning as synonymous with the burning of peat is preventing an appropriate analysis of the effects on carbon budgets over burning cycles and in the comparison of managed burning and wildfire effects on carbon fluxes[60].

xx. Public policy is not adapting to new evidence. Recent reports suggest much sequestered peatland carbon will not become part of the long term store[138,139], yet public policy on carbon budgets states that "*peatland … can continuously accumulate carbon under water-logged conditions at a rate of around 1mm per year*"[140]. See also Appendix 1 of GWCT Peatland Report 2020[8].

xxi. There remains a clear need for better data on long term carbon stocks, fluxes and how these are affected by wetting and burning, and for a more flexible interpretation and implementation of findings through management[8,137]. Currently the available data is just from a few sites and must be interpreted with caution.

Opportunities

xxii. Research suggests that some peatlands may naturally restore without management intervention resulting in the re-vegetation of bare peat areas[141] where climate and local topographic conditions are favourable[131]. See also Box 4.1.5.4 in the main report[o].

xxiii. There is still insufficient data to judge when restoration projects result in the conversion of a peatland from source to sink. Recent additions at the peatland surface do not indicate that the peatland as a whole is a C sink – "*the addition of new mass needs to exceed all losses throughout the whole profile for this to be the case*"[138]. Research into when and if a restored peatland becomes a carbon sink also needs to include the identification of appropriate metrics to monitor success.

xxiv. Carbon cycling relies on the soil microbiome yet little is understood about the process involved and how this affects peatland resilience and function. Given that climate change could alter soil conditions (predominantly the water table), understanding the impact that this will have on microbial processes is important. Microbial processes may be a way of monitoring peatland restoration success[142].

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[o] https://www.gwct.org.uk/englishgrousemoors

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