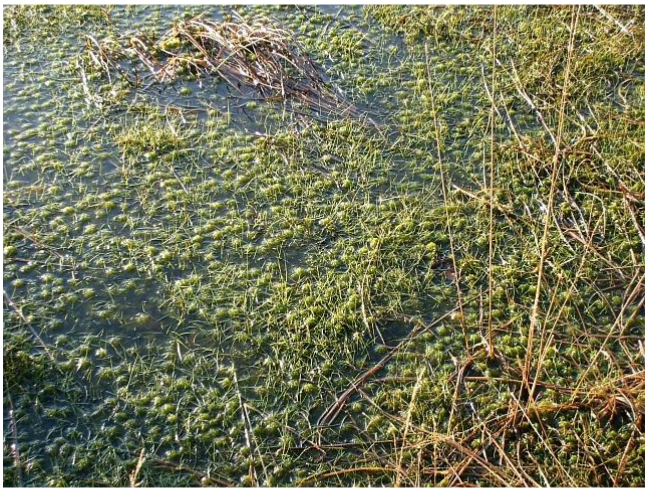
UK Parliament POST

POSTNOTE

Number 668 April 2022

Reducing peatland emissions



Peat soils store greenhouse gases for millennia if they stay waterlogged.[1,2] However, an estimated 5% of global greenhouse gas emissions are released from peat soils due to their modification by humans.[3] Reducing these emissions will help meet climate targets, with objectives to achieve this set out in action plans by the governments of the UK.[4] This POSTnote describes the pressures on peat soils, summarises the challenges for reducing emissions from English peatlands.

Overview

- Where waterlogging prevents the decomposition of plant matter it accumulates as a peat store of carbon.
- This stored carbon is emitted as greenhouse gases from peat soils when they are drained to lower water levels and managed for land uses such as agriculture and forestry.
- Drained lowland peat soils used for arable and horticulture crops are the largest sources of emissions from any land use in England. Climate change may increase emissions from peat soils in poor condition.
- Raising water levels and restoring peat forming conditions can reduce emissions.
- Monitoring the condition and outcomes of peatland restoration projects will be key for determining national emission reductions. At the project level, verified estimates of emission reductions from restoration are needed to access private carbon finance.
- Public grants require projects to secure partial funding from the private sector.

Emissions from peatlands

Peatland is an area with a substantial layer of partially rotted organic matter at or near the surface accumulating under waterlogged conditions, from plants such as *Sphagnum* mosses (Box 1).[5] This peat contains little solid matter and is around 90% water by volume when saturated.[6] The International Mire Conservation Group define peat layers of 15cm or more, with 5% organic matter or more, as significant stores of carbon;[5] shallow peat soils of 30cm store 327 tonnes of carbon per ha.[7] When peat bogs are drained for uses such as agriculture or forestry, greenhouse gases (GHGs) are emitted. With drainage and drying out, peat rapidly decomposes, compacts, subsides, shrinks and emits GHGs (Box 1).[8] Other processes can also contribute to peat loss and subsidence, such as wind and water erosion. These processes reduce peat depth until the remaining peat layer is thin and intermixed with the underlying mineral material ('wasted').[6,8]

The 2013 Intergovernmental Panel on Climate Change (IPCC) wetland supplement sets out the process used to calculate the GHG emissions (CO_2, CH_4 and N_2O, PN 662) from waterlogged organic soils modified by human activities.[9,10] More than 25% of global land use, land use change and forestry GHG emissions are from peat degradation,[11] with the Global Peatland Initiative currently mapping the extent, status and remaining carbon content of peatlands.[12] UK peatland 2019 GHG emissions were estimated at 23.1 million tonnes carbon dioxide equivalent (Mt $CO_2e\ yr^{-1}$),[13] adding 3.5% to total emissions.[14] Only 22% of UK peatlands are considered to be in a near natural state and storing rather than emitting carbon (less than 13% in England).[10,15,16] Nutrient poor peat bogs in upland areas waterlogged by rainfall (Box 2) comprise around 85% of the UK peatland resource.[17,18] However, England has a higher proportion of lowland peatland areas (44%) of nutrient rich fens and raised bogs (Box 2) than other UK nations, which account for more than 80% of its peatland emissions.[19] GHG emissions from English peatlands are estimated to be 11.1 Mt $CO_2e\ yr^{-1}$.[10] Including shallower peat soils (between 10 cm and 40 cm), there is approximately 1,420,000 ha of peatland in England,[16] with 124 landowners owning about 60% of this.[20]

The Parliamentary Office of Science and Technology, Westminster, London SW1A 0AA
02072192840 post@parliament.uk parliament.uk/post @POST_UK

Box 1: Peat formation

Peat soils consist of semi-decomposed plant (organic) material mixed with varying but small amounts of mineral (inorganic) matter.[19,21] Peat forms when the amount of plant material being added exceeds the rates of decomposition (accumulating at a rate of less than 2mm a year[22]).[23,] This occurs in waterlogged conditions and when vegetation isn't removed by cutting or grazing. Whether the water is nutrient rich or poor influences the vegetation present. Nutrient poor acidic waters will increase presence of *Sphagnum* mosses (bog mosses), but other mosses, sedges, grasses and woody plants may be sources of plant material.[24,25] The surface layer of peat-forming vegetation is referred to as the acrotelm and is generally between 10 cm and 40 cm deep. The relatively inert, permanently waterlogged peat store of organic carbon is referred to as the catotelm and can be metres deep.[19] The catotelm is classified according to the degree of decomposition (or 'humification') by microbes that occurs beforehand to the plant material in the acrotelm.[26]

Restoring peatlands can both reduce emissions and the interlinked loss of nature that depends on them (PN 617).[27]

Pressures driving peatland degradation

Data from existing and new UK monitoring studies have provided evidence for more accurate GHG emission estimates for the different uses and condition of peatlands.[10,28,29] These are higher than those based on the IPCC supplement.[30] With their inclusion in the national GHG inventory in 2019, land use changed from being a net sink to a net source of emissions.[31] The 2017 peatland emissions inventory classified peat in England as either deep or wasted, and into more detailed categories reflecting the extent to which they have been modified by humans. Bare and eroding peat has the highest levels of emissions, but better monitoring data could more precisely link peat condition and depth to emissions.[10,30,32]

Drainage for agriculture and afforestation

The condition of peat depends on its saturation. Systematic drainage of lowland peat began in the 17th Century in England, and only 16% still has a depth greater than 40 cm.[33,6] Approximately two thirds of the 325,000 ha of lowland peatlands in England are now classed as 'wasted'.[34] Such peatlands are often classed as Grade 1 or 2 Agricultural Land, reflecting their potential for cropping.[24] For instance, 10% of the national areas given to potatoes, sugar beet and vegetables are located in the Fenlands.[6,35] The drained lowland peat used for horticulture, cereal production and grazing, typically loses 1 to 3 cm of peat per year,[10] and estimated GHG emissions for lowland peat are 10 times higher than for upland peat.[6,35]

Upland drainage and burning

Upland blanket bogs (Box 2) in the UK have been modified to improve their productivity for livestock and game birds. Drainage via grips (open, shallow drains) were dug into the peat through the 20th century, peaking in the 1960/70s in response to government subsidies, with the aim of increasing grass coverage for grazing.[36] Controlled fire (managed burning) is also used to generate vegetation growth affecting around 30% of English blanket bog (PN-603).[15] The Government introduced legislation to ban burning on deep peat (>40cm) in Special Areas for Conservation and Special Protected Areas in England in 2021 and is considering extending the legislation.[40-42] Natural England, the Climate Change Committee (CCC) and the International Union for Conservation of Nature (IUCN) have stated that managed burning is likely to be detrimental to peat formation (Box 1) and carbon stocks.[15,43,44] The evidence that the practice is as detrimental as claimed is contested by some researchers and the Uplands Partnership (of organisations representing sporting estates and landowners), who suggest its use reduces wildfire risks. Contrary views are held by other researchers and environmental NGOs.[45-61]

Box 2: Blanket bogs, raised bogs and fens

The UK contains around 9-15% of Europe's peatland,[37] with three main types of peatland habitat in England:[19]

- **Blanket bog** forms on flat or gently sloping land under conditions of high rainfall and cloud cover, as found in the uplands of North and West England.[15] These are acidic and low nutrient habitats that accumulate peat slowly and are typically 0.4 to 6m deep. They have the lowest carbon density of the three types but the greatest extent,[15] with an estimated 355,000 ha of blanket bogs,[38] occurring within a mosaic of other habitats, such as heathland.[39]
- **Raised bog** usually form in lowland areas where a lack of drainage results in wetland habitat. As peat accumulates over time, it forms a dome of deep peat soil raised above the surrounding landscape and becomes acidic leading to Sphagnum dominated vegetation communities. There are only 35,000 ha in England; although the peat has a high carbon density, much has been degraded and drained.[15]
- **Fens** are comprised of wetlands that are fed by nutrient rich surface and groundwaters (PB 40). Fen types range from acidic and nutrient poor to those that are nutrient rich and may have the highest carbon density.[24] They support a diverse range of plants and animals and occur in mosaics with other habitats, such as wet woodland. In England, 24,000 ha of semi-natural fen and reedbed habitat remains and 194,100 ha has been drained for agriculture.[15]

Forestry

Incentivised by changes in taxation, between the late 1940s and early 1990s large areas of upland peatland were ploughed and planted with conifers.[62,38] This planting typically involved drainage, to lower water levels, and disturbance of peat layers during ground preparation and planting.[63] Research on birch and Scots pine trees suggests this results in emissions exceeding any captured by subsequent tree growth.[64] Despite removal and restoration starting in the 1990s, around 15% of UK peatlands are forested (5% in England).[18,17]

Extraction

Peat has also been directly extracted ('cut') for use in professional and retail horticulture. Industrial peat extraction now only occupies 0.15% of UK peatland, mostly on lowland raised bogs.[65] Extraction requires stripping away the vegetation and drainage of the bog, with the carbon emitted by this and the subsequent uses of the peat.[22] Quantities extracted in England have declined since 2003,[18] and is mainly restricted to the Somerset Levels. The CCC have advised ending peat extraction,[4] and the Government has consulted on legislation to ban the sale of peat and peat based products.[44,66]

Pollution

Air pollutants had a major impact on peatlands during the 19th and much of the 20th century.[67] For example, sulphur dioxide, an atmospheric pollutant from fossil fuel combustion, was deposited on upland peat increasing its acidity and forming sulphur compounds that were toxic for sphagnum.[68] Some upland peatland areas near urban areas were also contaminated with heavy metals, such as lead,[69] cadmium and zinc, from industrial activities.[70] These historic emissions have left a legacy of bare eroding peat,[69] acidified to the extent that the germination and growth of vegetation is inhibited.[71] Bare peat has higher rates of erosion, with the peat and dissolved organic matter washed into watercourses and decomposing to release CO_2.[72-74] Deposition of nitrogen pollutants (PN 458) arising from agricultural and fossil fuel combustion remain at levels that would be expected to be adverse for *Sphagnum* mosses and other plant species, inhibiting peat formation.[75-77]

Climate change

Most UK peatland formed under the climate conditions of the last 8,000 to 10,000 years.[78,79] Climate modelling suggests there will be increased variability in rainfall patterns, with high intensity summer rainfall events and less predictable levels of winter rainfall.[80] Although uncertainties remain, greater variability in precipitation and higher summer temperatures are likely to affect upland blanket bog peatland in areas with higher rainfall and lower temperature, reducing peat formation and increasing emissions.[81,79,15,82] A greater number of droughts may increase wildfire risks.[83-85] There have been significant wildfires in upland peatlands in recent years.[83,86-89] Wildfire damage to peat is greater in drained areas than in areas with a higher water table.[88,90] Researchers have suggested that raising water levels protects peat carbon stores from wildfire,[91-93] but others contend this will insufficient.[47] Restoration is expected to increase resilience to changes in climate.[94] For example, a layer of sphagnum moss provides water storage, raising the moisture levels of peat and keeping the water table closer to the surface.[93] However, shallow peat soils (less than 30cm) are most at risk from drought impacts and are slower to recover.[95]

Challenges for Restoring Peatlands

The CCC recommends restoring 55 to 70% of UK peatland by 2050, in order to reduce emissions by 4 to 11 $MtCO_2e$ a year.[96] The ONS estimate restoring 55% of peatland would deliver between £45 to £51 billion of climate benefits.[18] All the governments of the UK have consulted on, or are implementing, restoration programmes.[97] Under the Peatland Action Plan the Scottish Government has committed to restoring 250,000 ha by 2030, with 25,000 ha already under restoration and 6,000 ha per annum being restored at present.[98-100] In line with the 25 Year Environment Plan,[101] the 2021 England Peat Action Plan aims to restore 35,000 ha of peatland by 2025 funded with 50m from the Nature for Climate Fund (and 280,000 ha by 2050), with an annual target of 4,700 ha.[102-104] Over 22% of England's peatlands are already under restoration management, particularly blanket and raised bogs.[18] Established restoration programmes in England include the Great North Bog Partnership. Over the last 20 year they have restored 11,000 ha,[105] with partners such as Moors for the Future evolving the restoration evidence base for their area.[106]

However, data regarding the restoration of peatlands to reduce GHG emissions under specific contexts remains limited;[107] the time period for achieving reductions will depend on the extent of degradation and the previous land use.[108,109] Up-to-date, straightforward national guidance on evidence-based restoration techniques for the objective of reducing GHG emissions is lacking.[27] While individual landowners, organisations and contractors may have extensive knowledge about their restoration projects, this has not been integrated into a wider understanding. The Peatland Monitoring and Research Group provides advice to the Scottish National Peatland Group on knowledge gaps,[99] and Defra are considering forming a stakeholder advisory group.

Restoring water levels and vegetation

Re-establishing a waterlogged state should halt the loss of peat and reduce emissions.[109] Evidence suggests raising water levels is the single most important measure for reducing CO_2 emissions,[110] protecting carbon stores and restoring peat formation.[110-112] This can be achieved through methods such as drain blocking, but an evolving toolbox of other methods can be used depending on the type of peatland and previous use or damage.[113] For example, eroded complexes of upland blanket bog on slopes may be difficult to rewet,[114] due to factors such as underground erosional networks and may require stabilisation.[115-117,15] If peat remains bare, it will erode leading to GHG emissions. Straw or heather brash can be used to protect peat and reduce loss of moisture while *Sphagnum* establishes and erosion gullies blocked.[113] Grasses, lime and fertiliser have also been used to stabilise contaminated bare peat, followed by introduction of sphagnum,[118,119] but long-term studies are needed for data on restoration outcomes.[120,121] Dominance by purple moor grass can also lower water tables in blanket bogs.[122] Drain blocking alone is insufficient to reverse this,[115] but rewetting can be combined with *Sphagnum* planting.[123,124] Forestry can change the chemistry of upland peat and techniques that flatten and block furrows and remove as much as possible of the tree residues result in more rapid recovery than previous more minimal approaches.[63,125]

When peat is initially rewetted, GHG emissions (CH_4 and N_2O) can increase.[126] This due to changes in microbial communities (PN 601) that remain poorly understood,[126-128] particularly when water levels fluctuate,[129] around vegetation such as rushes on degraded peat or in ditches.[115,130] Studies have suggested emissions can potentially be reduced with wood chips containing high levels of phenolic compounds to inhibit decomposition,[131] by topsoil removal,[132] as well as avoiding water level fluctuations.[129] There is less evidence for restoration success in shallow peatlands, with evidence suggesting longer time frames are required.[95] Raised bogs may also require additional measures to slow water movement through damaged peat layers.[133] Restoring lowland fens may require removing top soil because of high levels of nutrients from agriculture (PN 662),[134] and additional measures to maintain water levels.[135] However, the evidence on the effects of these techniques on the wider environmental benefits peatlands provide is limited.[136]

Land use transitions

The CCC have recommended rewetting 72,000 ha of lowland peat soils used for crops and 54,000 ha used for grazing in England by 2035.[4] Options for rewetting are being considered by Defra's Lowland Agricultural Peat Task Force, which has four regional area sub-groups to consider the different contexts and uses and a sub-group on the options for wet agriculture (usually referred to as 'paludiculture'). Pilot projects are developing approaches to fen restoration,[137] but simply raising water levels would reduce emissions,[138] with the maximum reduction achieved if raised to 10cm below the soil surface.[111] This would change land uses,[6] but possible alternative wetland crops are being considered, such as sphagnum to supply as a growing medium for horticulture or crops for bioenergy or building materials. This may require transition funding for machinery and establishing new crops, products and markets.[139-144] Lowland or upland land use transitions also require integrated approaches to land and water management that consider trade-offs,[145] such as between food production and climate mitigation in lowland peatlands. It also requires incorporating the values and identities of landowners and local communities into the vision for the landscape (PB 42),[146,147] which the conflict over managed burning suggests may be challenging.[57] Research for Defra found the framing of peatland recovery or rewetting messages should reinforce place based identities of landowners, asking them to contribute their expertise and knowledge for the benefit of their communities.[148] The Southwest Peat Partnership, has set up partnerships for Bodmin, Exmoor and Dartmoor to involve government agencies, NGOs, landowners and farmers in peatland restoration plans.[144]

Mapping the extent and condition of peatlands

The UN Food and Agriculture Organisation has called for standardised definitions and approaches to mapping the extent and condition of peatland.[150] Previous UK peat maps have relied on ground surveys undertaken 30 or more years ago with varying mapping methodologies.[150] In Scotland, a mapping tool was developed to summarise information on peatland locations and their condition to indicate restoration target areas.[151] A new peat map for England to map the extent and depth England will be completed in 2024,[152] including shallow peat (between 10 cm and 40 cm). Previous UK policy definitions of peat soils used depth thresholds of 40cm in England,[42] and 50cm in Scotland (which differs from other countries).[153,154] Estimates of total peatland carbon stores remain uncertain due to peat depth variation over short distances.[38,15,155] Upland moors may also be a mosaic of bog and heath, with drained bogs containing similar plant species to heaths.[156]

Monitoring restoration trajectories

The recovery trajectory of a peatland will depend on its initial condition, climate, gradient and elevation and can be assessed using indicators such as water table depth.[157,158,95,121] This may require expertise; the House of Lords Science and Technology Committee have recommended establishing a training programme for land managers for relevant skills as well as a dedicated advisory service to engage them with the opportunities and provide support.[159] A standardised monitoring protocol could be incorporated into projects to provide data on outcomes and benefits. However, monitoring costs are not included in restoration funding at present and there is a lack of monitoring data on outcomes or restoration costs in different contexts.[160] Different national monitoring approaches are being implemented: England will rely on vegetation surveys initially; in Wales; a network of reference peatland sites in good condition will be used to assess progress; whereas Scotland is piloting a remote sensing approach (Box 3).

Public and private restoration finance

The Nature for Climate peatland grant scheme (NCPGS) requires projects to secure 25% of funds from the private sector.[170] Carbon finance requires estimating current GHG emissions and a prediction of future reductions/removal and involve two types of credits. Pending issuance units (PIUs) are based on expected GHG emission changes that have not happened yet. These can be sold to raise funds or retained until they are independently verified and converted to more valuable carbon units that meet GHG reporting requirements.[171,172] The IUCN UK Peatland Programme develop and manage the Peatland Code for accessing private finance,[173] with 12,357 ha of peatland currently registered. It requires an initial restoration plan to be validated, an emissions baseline to be determined from the initial peatland condition and from this the expected net change in GHG emissions over the duration of project calculated.[174,159,175,] Risk and leakage buffers (15 and 10%) are then used to determine how much of the expected net change can be sold as PIUs. Verification of restoration activities to reduce GHG emissions is needed within a year, after 5 years and then every 10 years for a minimum project duration of 30 years.[176] Other options for public funding leveraging private investment include a carbon floor price guarantee mechanism, which is used for Woodland Carbon Code projects (PN 636).[177]

Box 3: Remote sensing of peatland condition

The surface of a functioning peat bog will swell and shrink with changes in the volume of water and gas through the year ('bog breathing').[161,162] This surface motion can be measured with remote sensing approaches (PN 628).[163] Researchers have been developing a methodology since 2016 with NatureScot, testing the methodology at different sites.[164,88] This includes a method to determine surface dynamics and a new statistical method for faster analysis. It can provide an assessment of the existing baseline condition over a large area, measure change in condition and provide data on the probability of changes in that condition. There have been a range of other developments on the use of different remote sensing technologies that could be part of a monitoring toolkit,[165,160] such as methods for monitoring habitat change, wetness and peat depth.[166-169]

The Environmental Land Management Scheme is replacing NCPGS in 2025 as the public finance source. Various approaches could be used for blending public and private carbon finance and avoiding them competing,[178,179] but some projects will have a high cost per tonne of carbon emissions reduction. There are several successful ecosystem benefit marketplaces that could be an additional source of finance (PN 661 and 636). For example, various water companies have involvement in projects to protect water resources through habitat restoration in upland areas, such as South West Water's Upstream Thinking,[180] which is part of the Southwest Peat Partnership.[149] Peatlands support a range of environmental benefits and wildlife.[2,139,6,179,181] For instance, compared to areas of bare and eroded peat, a rough surface of *Sphagnum* will slow the flow of surface water and may absorb water,[182] reducing the rate by 30 to 40% during intense summer rainfall events and mitigating flood risks (PN 623).[95,116] The House of Lords Science and Technology Committee recommended the inclusion of such environmental co-benefits in the Peatland Code.[159] For example, the MoorFutures 2.0 regional German carbon market have integrated other environmental benefits into the carbon credits issued by the State's Ministry for Environment and Agriculture.[183]

1. IUCN (2021). Peatlands and climate change issues brief.
2. Bonn, A *et al.* (2016). Peatland Restoration and Ecosystem Services: Science, Policy and Practice. Cambridge University Press.
3. United Nations Environment Programme (2021). Economics of Peatlands Conservation, Restoration, and Sustainable Management - A Policy Report for the Global Peatlands Initiative.
4. CCC. 2021 Progress Report to Parliament. *Climate Change Committee*.
5. Joosten, H. 2021, International Mire Conservation Group - Bulletin. Issue 03 21, p.20-23
6. Page, S, et al. (2020). Societal Impacts Report - March 2020.pdf. CEH
7. Lindsay, R. *et al.* (2019) Peatlands: the challenge of mapping the world's invisible stores of carbon and water. UNASYLVA, Vol 70, 12.
8. IUCN UK Committee Peatland Programme (2014). Impacts of Artificial Drainage on Peatlands, Briefing Note 3.pdf.
9. IPCC. 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands - IPCC-TFI.
10. Evans, C. *et al.* (2017). Implementation of an Emissions Inventory for UK Peatlands. Centre for Ecology and Hydrology.
11. Tubiello, F. N. *et al.* (2016). A Worldwide Assessment of Greenhouse Gas Emissions from Drained Organic Soils. *Sustainability*, Vol 8, 371.
12. Global Peatlands Initiative
13. BEIS. (2019). 2019 UK Greenhouse Gas Emissions, Final Figures.
14. IUCN Peatland Programme, Peatland addition to the UK GHG inventory adds 3.5% to national emissions. .
15. Gregg, R, *et al.* (2021). Carbon Storage and Sequestration by Habitat 2021 - NERR094. .
16. HM Government. England Peat Action Plan.
17. JNCC. 2011. Towards an assessment of the state of UK peatlands, JNCC Report No. 445.
18. UK natural capital - Office for National Statistics.
19. IUCN UK Committee Peatland Programme (2014). Peat Bog Ecosystems: Key Definitions, Briefing Note 1.
20. Shrubsole, G. (2021). Who-owns-our-carbon-nov-2021.pdf.
21. NatureScot. (2016). Carbon rich soil, deep peat and priority peatland habitat mapping.
22. IUCN UK Committee Peatland Programme (2014) Commercial peat extraction, Briefing Note 6.
23. FAO (2014). Towards climate-responsible peatlands management. FAO.
24. Morris, J. *et al.* (2010). Restoration of Lowland Peatland in England and Impacts on Food Production and Security. Report to Natural England. Cranfield University.
25. CEH. Lowland Peat.
26. Zaccone, C. *et al.* (2018). Advances in the determination of humification degree in peat since Achard (1786): Applications in geochemical and paleoenvironmental studies. *Earth-Science Reviews*, Vol 185, 163–178.
27. Stafford, R. *et al* (Eds.) (2021). Nature-based Solutions for Climate Change in the UK: A Report by the British Ecological Society.
28. *ClimateXChange*. NB18 Annual greenhouse gas (GHG) emissions from degraded peatlands.
29. Smyth, M.-A. *et al.* (2013). A bog standard way of estimating greenhouse gas emissions from UK peatlands, by Dick Birnie and Mary-Ann Smyth. *The Heather Trust Annual Report*,
30. BEIS. (2019). Mapping Carbon Emissions & Removals for the Land Use, Land-Use Change & Forestry Sector. A report of the National Atmospheric Emissions Inventory 2019.
31. Gabbatiss, J. (2021). Analysis: How will England's strategies for trees and peat help achieve net-zero by 2050? *Carbon Brief*.
32. Wilson, D. *et al.* (2016). Greenhouse gas emission factors associated with rewetting of organic soils. *Mires and Peat*, 1–28.
33. Ash, E. H. (2016). Reclaiming a New World: Fen Drainage, Improvement, and Projectors in Seventeenth-Century England. *Early Science and Medicine*, Vol 21, 445–469.
34. Johnson, S. *et al.* (2019). Productive Lowland Peatland.pdf.
35. Graves, A. and Morris, J. (2013). Restoration of Fenland Peatland under Climate Change. Report to the Adaptation Sub-Committee of the Committee on Climate Change. Cranfield University.
36. Wilson, L. *et al.* (2011). The effect of blanket bog drainage on habitat condition and on sheep grazing, evidence from a Welsh upland bog. *Biological Conservation*, Vol 144, 193–201.
37. IUCN UK Commission of Inquiry on Peatlands Summary of Findings.
38. Natural England. (2010). England's peatlands: carbon storage and greenhouse gases - NE257.
39. Littlewood, N. *et al.* (2010). Peatland Biodiversity, Scientific Review for the IUCN UK Peatland Programme.
40. Natural England, Special Areas of Conservation (England). Open Data Publication
41. Scott, E. (2021). Peatland burning: New regulations for blanket bog habitats. House of Lords Library
42. The Heather and Grass etc. Burning (England) Regulations 2021.
43. IUCN UK Committee Peatland Programme (2014). Burning, Briefing Note No. 8.
44. CCC. (2020). Land use: Policies for a Net Zero UK. *Climate Change Committee*.
45. The Uplands Partnership. (2021). Peatland Protection.
46. Ashby, M. *et al.* (2020). Prescribed burning impacts on ecosystem services in the British uplands: A methodological critique of the EMBER project. *Journal of Applied Ecology*, Vol 57, 2112–2120.
47. Ashby, M. *et al.* (2021). A Critical Review of the IUCN UK Peatland Programme's "Burning and Peatlands" Position Statement. *Wetlands*, Vol 41, 56.
48. Davies, G. *et al.* (2016). The role of fire in UK peatland and moorland management: the need for informed, unbiased debate. *Philosophical Transactions of the Royal Society B: Biological Sciences*, Vol 371, 20150342.
49. Heinemeyer, A. *et al.* (2018). Peatland carbon stocks and burn history: Blanket bog peat core evidence highlights charcoal impacts on peat physical properties and long-term carbon storage. *Geo: Geography and Environment*, Vol 5, e00063.
50. Heinemeyer, A. *et al.* (2019). Response to: Comment on "Peatland carbon stocks and burn history: Blanket bog peat core evidence highlights charcoal impacts on peat physical properties and long-term carbon storage" by Evans et al. (Geo: Geography and Environment 2019; e00075). *Geo: Geography and Environment*, Vol 6, e00078.
51. Ashby, D. M. A. *et al.* (2019). Whither scientific debate? A rebuttal of "Contextualising UK moorland burning studies: geographical versus potential sponsorship-bias effects on research conclusions" by Brown and Holden (bioRxiv 2019; 731117). EcoEvoRxiv.
52. Whitehead, S. *et al.* (2021). Post-burning responses by vegetation on blanket bog peatland sites on a Scottish grouse moor. *Ecological Indicators*, Vol 123, 107336.
53. Leifeld, J. *et al.* (2018). Pyrogenic Carbon Contributes Substantially to Carbon Storage in Intact and Degraded

Northern Peatlands. *Land Degradation & Development*, Vol 29, 2082–2091.

54. Harper, A. *et al.* (2018). Prescribed fire and its impacts on ecosystem services in the UK. *Science of The Total Environment*, Vol 624, 691–703.
55. Brown, L. E. *et al.* (2020). Contextualizing UK moorland burning studies with geographical variables and sponsor identity. *Journal of Applied Ecology*, Vol 57, 2121–2131.
56. Evans, C. D. *et al.* (2019). Comment on: "Peatland carbon stocks and burn history: Blanket bog peat core evidence highlights charcoal impacts on peat physical properties and long-term carbon storage," by A. Heinemeyer, Q. Asena, W. L. Burn and A. L. Jones (Geo: Geography and Environment 2018; e00063). *Geo: Geography and Environment*, Vol 6,
57. Zimmermann, A. *et al.* (2021). Deliberating Our Frames: How Members of Multi-Stakeholder Initiatives Use Shared Frames to Tackle Within-Frame Conflicts Over Sustainability Issues. *J Bus Ethics*,
58. Wildlife and Countryside Link. Partial peat-burning ban a positive first step, but limits and loopholes leave cause for climate concern. .
59. Moorland Peat Burning. *The RSPB*.
60. Holden, J. *et al.* (2015). Impact of prescribed burning on blanket peat hydrology. *Water Resources Research*, Vol 51, 6472–6484.
61. Wild Moors. Burning issue: councils unite to save England's peatlands.
62. IUCN UK Committee Peatland Programme. Ecological Impacts of Forestry on Peatlands – Briefing Note 4.
63. Campbell, D. *et al.* (2019). Peatlands and Forestry. Review for the IUCN UK Peatland Programme's Commission of Inquiry on Peatlands.
64. Friggens, N. L. *et al.* (2020). Tree planting in organic soils does not result in net carbon sequestration on decadal timescales. *Global Change Biology*, Vol 26, 5178–5188.
65. CEH. Peatland factsheet.
66. GOV.UK. Ending the retail sale of peat in horticulture in England and Wales.
67. Andersen, R. *et al.* (2017). An overview of the progress and challenges of peatland restoration in Western Europe. *Restoration Ecology*, Vol 25, 271–282.
68. IUCN UK Committee Peatland Programme. Atmospheric pollution – Briefing Note 13.
69. Rothwell, J. J. *et al.* (2005). Heavy metal release by peat erosion in the Peak District, southern Pennines, UK. *Hydrological Processes*, Vol 19, 2973–2989.
70. Crouch, T., Walker, J. and Morley, K. (2015) Peatland Restoration Project: Rivers Alport and Ashop Monitoring Report. Moors for the Future Partnership, Edale.
71. Sjm, C. *et al.* (2006). Recovery of ombrotrophic Sphagnum mosses in relation to air pollution in the Southern Pennines. Report to Moors for the Future Partnership.
72. Moors for the Future Partnership, Improving water quality.
73. Li, C. *et al.* (2018). Erosion in peatlands: Recent research progress and future directions. *Earth-Science Reviews*, Vol 185, 870–886.
74. Pickard, A, *et al.* (2022). Effects of peatland management on aquatic carbon concentrations and fluxes. Biogeosciences, 19, 1321–1334
75. Sheppard, L. J. *et al.* (2014). Inertia in an ombrotrophic bog ecosystem in response to 9 years' realistic perturbation by wet deposition of nitrogen, separated by form. *Glob Chang Biol*, Vol 20, 566–580.
76. Field, C. D. *et al.* (2014). The Role of Nitrogen Deposition in Widespread Plant Community Change Across Semi-natural Habitats. *Ecosystems*, Vol 17, 864–877.
77. Evans, C. D. *et al.* (2014). Contrasting vulnerability of drained tropical and high-latitude peatlands to fluvial loss of stored carbon. *Global Biogeochemical Cycles*, Vol 28, 1215–1234.
78. Loisel, J. *et al.* (2021). Expert assessment of future vulnerability of the global peatland carbon sink. *Nat. Clim. Chang.*, Vol 11, 70–77.
79. Gallego-Sala, A. V. *et al.* (2010). Bioclimatic envelope model of climate change impacts on blanket peatland distribution in Great Britain. *Climate Research*, Vol 45, 151–162.
80. Berry, P. and Brown, I. (2021) National environment and assets. In: The Third UK Climate Change Risk Assessment Technical Report [Betts, R.A., Haward, A.B. and Pearson, K.V. (eds.)]. Prepared for the Climate Change Committee, London.
81. Hanson, P. J. *et al.* (2020). Rapid Net Carbon Loss From a Whole-Ecosystem Warmed Peatland. *AGU Advances*, Vol 1, e2020AV000163.
82. Natural England and RSPB. (2019). Climate Change Adaptation Manual - Evidence to support nature conservation in a changing climate, 2nd Edition - NE751.
83. Belcher, C. M. *et al.* (2021). UK wildfires and their climate challenges. Expert Led Report Prepared for the third Climate Change Risk Assessment.
84. Deane, P. J. *et al.* (2020). Seismic Lines in Treed Boreal Peatlands as Analogs for Wildfire Fuel Modification Treatments. *Fire*, Vol 3, 21.
85. Lin, S. *et al.* (2021). Climate-induced Arctic-boreal peatland fire and carbon loss in the 21st century. *Science of The Total Environment*, Vol 796, 148924.
86. Glaves, D. *et al.* (2020). The causes and prevention of wildfire on heathlands and peatlands in England - NEER014. .
87. BBC News. (2019). Huge Flow Country wildfire 'doubled Scotland's emissions'. .
88. Gewin, V. (2020). How peat could protect the planet. *Nature*, Vol 578, 204–208.
89. UNEP. (2022). Spreading like Wildfire: The Rising Threat of Extraordinary Landscape Fires. *UNEP - UN Environment Programme*.
90. Davies, G. M. *et al.* (2016). Regional variation in fire weather controls the reported occurrence of Scottish wildfires. *PeerJ*, Vol 4, e2649.
91. IUCN UK Peatland Programme. (2021). Burning and Peatlands Position Paper.
92. Baird, A. J. *et al.* (2019). Validity of managing peatlands with fire. *Nat. Geosci.*, Vol 12, 884–885.
93. Granath, G. *et al.* (2016). Mitigating wildfire carbon loss in managed northern peatlands through restoration. *Sci Rep*, Vol 6, 28498.
94. Lunt, P. H. *et al.* (2019). Role of recent climate change on carbon sequestration in peatland systems. *Science of The Total Environment*, Vol 667, 348–358.
95. Brazier, R. *et al.* (2020) Mires on the Moors: Science and Evidence Report, University of Exeter.
96. Committee on Climate Change. (2018). Land use: Reducing emissions and preparing for climate change.
97. Pike, J. (2021). Peat and Peatlands. Northern Ireland Assembly Research and Information Service Briefing Paper.
98. Natural Resources Wales, The National Peatland Action Programme.
99. NatureScot. Scotland's National Peatland Plan: Working for our future.
100. DAERA. (2021). NI Peatland Strategy Consultation | Department of Agriculture, Environment and Rural Affairs.
101. HM Government. A Green Future: Our 25 Year Plan to Improve the Environment.
102. HM Government. England Peat Action Plan..
103. Great Britain *et al.* (2021). Net Zero Strategy: Build Back Greener.
104. Defra (2021). Annual Report and Accounts 2020–21.

105. The Great North Bog – The UK's Peatland Restoration Partnership.
106. Moors for the Future. Our Resources.
107. Bonnett, et al. (2011). A review of techniques for monitoring the success of peatland restoration - NECR086. *Natural England - Access to Evidence*.
108. Artz, R. *et al.* (2012). Potential Abatement from Peatland Restoration. Climate X Change.
109. IUCN UK Committee Peatland Programme, Peatland Restoration, Briefing Note 11.
110. Günther, A. *et al.* (2020). Prompt rewetting of drained peatlands reduces climate warming despite methane emissions. *Nat Commun*, Vol 11, 1644.
111. Evans, C. D. *et al.* (2021). Overriding water table control on managed peatland greenhouse gas emissions. *Nature*, 1–7.
112. Hambley, G. et al. (2019). Net ecosystem exchange from two formerly afforested peatlands undergoing restoration in the Flow Country of northern Scotland. Mires and Peat - Mires and Peat 23 | 05.
113. Taylor, N. et al. (2018). Peatland Conservation: Global Evidence for the Effects of Interventions to Conserve Peatland Vegetation.
114. Williamson, J. *et al.* (2017). Historical peat loss explains limited short-term response of drained blanket bogs to rewetting. *Journal of Environmental Management*, Vol 188, 278–286.
115. Gatis, N. *et al.* (2020). Drain blocking has limited short-term effects on greenhouse gas fluxes in a Molinia caerulea dominated shallow peatland. *Ecological Engineering*, Vol 158, 106079.
116. Parry, L. E. *et al.* (2014). Restoration of blanket peatlands. *Journal of Environmental Management*, Vol 133, 193–205.
117. Green, S. M. *et al.* (2017). An experimental study on the response of blanket bog vegetation and water tables to ditch blocking. *Wetlands Ecol Manage*, Vol 25, 703–716.
118. Caporn, S. J. M. *et al.* (2018). Sphagnum restoration on degraded blanket and raised bogs in the UK using micropropagated source material: a review of progress. *Mires and Peat*, 1–17.
119. Qassim, S. M. *et al.* (2014). A 5-year study of the impact of peatland revegetation upon DOC concentrations. *Journal of Hydrology*, Vol 519, 3578–3590.
120. Stimson, A. G. *et al.* (2017). Water quality impacts of bare peat revegetation with lime and fertiliser application. *Applied Geochemistry*, Vol 85, 97–105.
121. Alderson, D. M. *et al.* (2019). Trajectories of ecosystem change in restored blanket peatlands. *Science of The Total Environment*, Vol 665, 785–796.
122. England, N. Managing Molinia? Proceedings of a 3 day conference September 2015 - JP017.
123. Pilkington, M. *et al.* (2021). Diversification of Molinia-dominated blanket bogs using Sphagnum propagules. *Ecological Solutions and Evidence*, Vol 2, e12113.
124. D1-single-species-Sphagnum-report-final.pdf.
125. Hermans, R. *et al.* (2019). Climate benefits of forest-to-bog restoration on deep peat. Climate X Change Policy briefing.
126. Abdalla, M. *et al.* (2016). Emissions of methane from northern peatlands: a review of management impacts and implications for future management options. *Ecol Evol*, Vol 6, 7080–7102.
127. Ritson, J. *et al.* (2021). Towards a microbial process-based understanding of the resilience of peatland ecosystem service provisioning – A research agenda. *Science of The Total Environment*, Vol 759, 143467.
128. Ritson, J. *et al.* (2020). Microbial understanding of the resilience of peatland systems. *Peatland Microbiology Project*.
129. Kim, J. *et al.* (2021). Water Table Fluctuation in Peatlands Facilitates Fungal Proliferation, Impedes Sphagnum Growth and Accelerates Decomposition. *Frontiers in Earth Science*, Vol 8,
130. Köhn, D. *et al.* (2021). Drainage Ditches Contribute Considerably to the CH_4 Budget of a Drained and a Rewetted Temperate Fen. *Wetlands*, Vol 41, 71.
131. Alshehri, A. *et al.* (2020). A Potential Approach for Enhancing Carbon Sequestration During Peatland Restoration Using Low-Cost, Phenolic-Rich Biomass Supplements. *Frontiers in Environmental Science*, Vol 8,
132. Huth, V. *et al.* (2022). The climate benefits of topsoil removal and Sphagnum introduction in raised bog restoration. *Restoration Ecology*, Vol 30, e13490.
133. Moor, H. *et al.* (2016). Bringing Lowland Raised Bogs to Life. BogLife, Issue 2..
134. Klimkowska, A. *et al.* (2007). Wet meadow restoration in Western Europe: A quantitative assessment of the effectiveness of several techniques. *Biological Conservation*, Vol 140, 318–328.
135. restoring-hydrological-processes-paper.pdf.
136. Artz, R. *et al.* (2018). Peatland restoration – a comparative analysis of the costs and merits of different restoration methods. Climate X Change.
137. Care-Peat partnership. The Wildlife Trust for Lancashire, Manchester and North Merseyside.
138. Brandehof, J. (2020). Paying for peat: rewetting peatlands in the Netherlands. *Eurosite*.
139. Tanneberger, F. *et al.* (2021). The Power of Nature-Based Solutions: How Peatlands Can Help Us to Achieve Key EU Sustainability Objectives. *Advanced Sustainable Systems*, Vol 5, 2000146.
140. Jurasinski, G. *et al.* (2020). From Understanding to Sustainable Use of Peatlands: The WETSCAPES Approach. *Soil Systems*, Vol 4, 14.
141. MoorWissen. Paludi-PRIMA.
142. MoorWissen. OptiMOOS.
143. Tanneberger, F. *et al.* (2020). Climate Change Mitigation through Land Use on Rewetted Peatlands – Cross-Sectoral Spatial Planning for Paludiculture in Northeast Germany. *Wetlands*, Vol 40, 2309–2320.
144. Temmink, R. J. M. *et al.* (2017). Sphagnum farming in a eutrophic world: The importance of optimal nutrient stoichiometry. *Ecological Engineering*, Vol 98, 196–205.
145. Meyfroidt, P. *et al.* (2022). Ten facts about land systems for sustainability. *PNAS*, Vol 119,
146. Joint Research Centre (European Commission) *et al.* (2021). Values and identities: a policymaker's guide. Publications Office of the European Union.
147. Hewitt, M. (2022). UK-wide biodiversity renewal project receives £10m boost. *Environment Journal*.
148. Reed, M. *et al.* (2020). Social barriers and opportunities to the implementation of the England Peat Strategy. Final Report to Natural England and Defra, Newcastle University
149. South West Water. South West Peatland Partnership.
150. FAO. (2020). Peatlands mapping and monitoring.
151. Climate X Change. The WISE peatland tool.
152. UK Government. Natural Capital and Ecosystem Assessment Programme. *GOV.UK*.
153. Scottish Forestry. (2016). Supplementary guidance to support the FC Forests and Peatland Habitats Guideline Note (2000).
154. Joosten, H. *et al.* (2017). Mires and peatlands of Europe.
155. Lindsay, R. (2010). Peatbogs and carbon. A Critical Synthesis.
156. Moors for the Future. A mosaic of moorland habitats. .
157. Moors for the Future Partnership. (2013). Vegetation recovery on bare peat after restoration intervention: an analysis of nine years of monitoring data in the Dark Peak moorlands.

158. Renou-Wilson, F *et al*. (2018). Network Monitoring Rewetted and Restored Peatlands/Organic Soils for Climate and Biodiversity Benefits (NEROS). Report 236
159. House of Lords Science and Technology Committee. Nature-based solutions: rhetoric or reality? The potential contribution of nature-based solutions to net zero in the UK.
160. Artz, R. *et al.* (2019). The State of UK Peatlands: an update. Review for the IUCN UK Peatland Programme's Commission of Inquiry on Peatlands.
161. Howie, S. A. *et al.* (2018). Bog surface oscillation (mire breathing): A useful measure in raised bog restoration. *Hydrological Processes*, Vol 32, 1518–1530.
162. Morton, P. A. *et al.* (2019). Bog breathing: the extent of peat shrinkage and expansion on blanket bogs in relation to water table, heather management and dominant vegetation and its implications for carbon stock assessments. *Wetlands Ecol Manage*, Vol 27, 467–482.
163. Alshammari, L. *et al.* (2020). Use of Surface Motion Characteristics Determined by InSAR to Assess Peatland Condition. *Journal of Geophysical Research: Biogeosciences*, Vol 125, e2018JG004953.
164. NatureScot Research Report 1269 - Using peatland surface motion (bog breathing) to monitor Peatland Action sites. *NatureScot*.
165. The South West Partnership for Environmental and Economic Prosperity. Quantitative Habitat Mapping. .
166. Lightfoot, P. *et al.* (2021). Using Sentinel data to monitor change in habitats and historic landscape features. JNCC Technical Report for the Caroline Herschel Framework Partnership Agreement for Copernicus User Uptake.
167. Gatis, N. *et al.* (2019). Mapping upland peat depth using airborne radiometric and lidar survey data. *Geoderma*, Vol 335, 78–87.
168. Carless, D. *et al.* (2019). Mapping landscape-scale peatland degradation using airborne lidar and multispectral data. *Landscape Ecol*, Vol 34, 1329–1345.
169. Higginbottom, T. P. *et al.* (2018). High-resolution wetness index mapping: A useful tool for regional scale wetland management. *Ecological Informatics*, Vol 48, 89–96.
170. UK Government. Nature for Climate Peatland Grant Scheme. *GOV.UK*.
171. Emmer, I, and Couwenberg, J. (2017). VM0036 Rewetting Drained Temperate Peatlands. VCS Methodology
172. CarbonStore. Carbon Units Explained. .
173. IUCN Peatland Programme. Introduction to the Peatland Code. IUCN UK Peatland Programme. .
174. Andersen, R. *et al.* (2017). An overview of the progress and challenges of peatland restoration in Western Europe. *Restoration Ecology*, Vol 25, 271–282.
175. IUCN Peatland Programme. Peatland Code v1.1.
176. IUCN Peatland Programme. For Projects. IUCN UK Peatland Programme. .
177. UK Government. Woodland Carbon Guarantee. *GOV.UK*.
178. Environmental Finance and Ecosystems Knowledge Network. (2020). Emerging funding opportunities for the natural environment.
179. Reed, M. S. *et al.* (2022). Integrating ecosystem markets to co-ordinate landscape-scale public benefits from nature. *PLOS ONE*, Vol 17, e0258334.
180. Grand-Clement, E. *et al.* (2021). Upstream Thinking: Evaluating the impact of farm interventions on water quality at the catchment scale, University of Exeter.
181. RSPB. (2014). English upland peatlands – turning round a crisis.
182. Shuttleworth, E. L. *et al.* (2019). Restoration of blanket peat moorland delays stormflow from hillslopes and reduces peak discharge. *Journal of Hydrology X*, Vol 2, 100006.
183. Joosten, H. *et al*. (2015). MoorFutures. Integration of additional ecosystem services into carbon credits – standard, methodology and transferability to other regions. Federal Agency for Nature Conservation.