The State of UK Peatlands: an update

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In memory of Dr Richard Payne

September 2019

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Summary

This topic report provides an update on the 2011 JNCC report, focusing on new information obtained since its publication in relation to mapping of peat soil extent, land cover, condition and change. The report also outlines our current understanding of trajectories of change following restoration activities.

Mapping the UK peat resource

Since 2011, several major updates have been made to national peat maps for all of the UK countries except England. In Scotland, the existing James Hutton Institute (JHI) peat map has been revised in order to replace the existing 'probabilistic' map with a modelled spatially explicit map of peat presence/absence, enabling the peat map to be combined with land cover data to support peat condition assessment and monitoring. In Wales, the Welsh Government has supported the development of a completely new peat map, utilising detailed mapping data from the British Geological Survey (BGS) and Natural Resources Wales (NRW). In Northern Ireland, a new map has been produced by BGS based on their own mapping data, augmented by data from the Agri-Food and Biosciences Institute (AFBI) and the Northern Ireland Peat Survey data. In addition, BGS data have been used to map peat extent in the Isle of Man, and to support a new (provisional) estimate of peat extent in the Falkland Islands. This estimate will be refined during a new Darwin Plus project to create the first complete Falkland soil extent and condition map, which is being led by the South Atlantic Environment Research Institute (SAERI). Overall, peat mapping activities since 2011 have expanded the estimated peat extent in the four UK countries to almost 3 million hectares, an increase of 276,500 ha over the 2011 estimate (Table 1 in Main Report). The estimated 282,000 ha of peat in the Falklands (larger than the total peat areas of either Wales or Northern Ireland) represents a substantial further addition to the estimated area of peat under UK jurisdiction.

Assessing peat condition

The assessment of peat condition in the 2011 JNCC report was largely based on land cover and habitat maps. These maps use different classification systems, are based on ground and/or satellite survey data collected at different times and cover all soil types so have only fairly coarse categories for peatland areas. Subsequent national-scale mapping activities have used aerial photography to disaggregate peatlands into different condition categories (England) or map drainage features (Wales, and in part for Scotland), while more detailed mapping has been undertaken in individual peatland regions such as Dartmoor and the South Pennines. Some of these more recent data were used in the recent development of the UK BEIS Emissions Inventory for Peatlands project (hereafter called the BEIS Inventory project), however inconsistencies between national and regional classification schemes, variations in the 'base year' in which surveys were taken, and in particular the absence of comparable repeat surveys still severely constrain the extent to which peat condition can be mapped and monitored at a national scale. There is still a need to create a national baseline map of condition for all peatland types across the whole UK that change can then be assessed against in future years. Even if a baseline for 1990 cannot be accurately reconstructed, an appropriate and nationally consistent effort to create an accurate 2020 baseline map would help future generations assess progress towards the 2040 target of the IUCN Peatland Strategy ("Two million hectares of peatland in good condition, under restoration or being sustainably managed by 2040").

The latest UK-wide update on trends in condition on peatland habitats was published in 2013 by the Joint Nature Conservation Committee[1]. This report suggests overall bad condition for all nine peatland habitat types under nature designation. Six of these habitats were considered to show an overall improving trend in condition status. The majority of improving habitats, however, are fen type habitats, which occupy a relatively small proportion of the total UK peatland habitat. The condition of most bog habitats, including that of blanket bog, was declining. However, such ground-based condition survey data place restrictions on consistent peatland assessment as there is a finite extent of peatland that can be reasonably assessed in a single year given financial limitation and repeat surveys themselves can cause a decline in local condition due to e.g. trampling. To increase the extent of monitoring and reduce ecological pressure on the ground, several recent and ongoing initiatives have sought to make greater use of Earth Observation (EO) data. The increasing spatial and temporal resolution of free of charge satellite data such as the European Space Agency's Sentinel 1 (radar) and 2 (optical) satellites is providing new opportunities for consistent, detailed and frequent peat assessment, which were explored as part of recent work for Defra and the Scottish Government (JNCC, unpublished). Case study assessments for the Flow Country, Pennines and North Wales show that these data have high potential to differentiate between different peat vegetation and condition categories, although the infrequency of cloud-free imagery for the UK uplands limits the use of optical data (radar data are less affected by cloud cover but provide less comprehensive information). A further constraint is the absence of field data collected at an appropriate spatial resolution to train satellite classification algorithms, which risks leading to inaccurate or regionally inconsistent assessments. Scottish Water also commissioned a study through Rezatec to map peatland integrity and risks to water quality in a number of drinking water catchments across Scotland and the Glastir Monitoring and Evaluation Programme as well as other smaller-scale assessments have used mapping of peatland condition from high resolution aerial photography sources, including drones.

Other relevant developments in the use of EO data include the use of Sentinel 1 radar data for i) crop mapping, which could in future be used to assess and monitor lowland areas under arable agriculture, ii) monitoring of near-surface soil moisture, as a proxy for drainage impacts or the resilience of restored areas during extreme climatic events, and iii) monitoring the vertical movement of peatlands using interferometry[2], as a measure of peat growth or subsidence, and also an indicator of hydrological functioning. As noted above, aerial photography data have already been used to map peat condition and ditch occurrence, although such approaches are laborious, partly subjective and expensive to repeat. High-resolution LiDAR elevation measurements have been used for ditch and erosion mapping, but again the cost of surveys limits their repeatability. Finally, there has been substantial growth in the use of Unmanned Aerial Vehicles (UAVs) for peat assessment. Given the limited extent and labour costs of UAV mapping it is unlikely that they can be used for national-scale assessments, however they represent a valuable tool for monitoring ecological change at the scale of individual restoration projects and such data have the potential to be used to train larger scale models to improve accuracy of EO outputs. A detailed and in-depth accurate assessment could be made of a variety of peatland areas, which could then be used to interpret satellite data to extrapolate out over all the peatland areas to a broader but slightly less accurate assessment of peat condition. The ecology, processes and threats to peatlands in the UK's Crown Dependencies and Overseas Territories, including the Falklands, are poorly described and understood and will require fundamental effort on the ground to establish appropriate baseline data.

Extent of restoration since 2011

The most recent UK-wide assessment of peat restoration activity, for the BEIS Inventory project, covered the period 1990 to 2013, and was based on a collation of information from 409 individual projects. This assessment gave an estimate that around 110,000 ha of peatland has been subject to some form of restoration intervention, of which 73,200 ha included active re-wetting, while the remainder

[1] Joint Nature Conservation Committee. 2013. Habitat Conservation Status Reports - 3rd UK Habitats Directive Reporting 2013 [online]. Available: http://archive.jncc.gov.uk/page-6563

[2] Interferometric synthetic aperture radar (InSAR) uses two or more SAR images to generate maps of surface deformation/digital elevation, by utilising the phase differences in the waves returning to the satellite. It can measure up to millimetre changes across a defined time period.

involved other forms of peatland management such as grazing reduction or scrub removal that may be contributing to 'passive' re-wetting (e.g. by lowering evapotranspiration losses). An additional 1 million ha of peatland has been included in some form of UK agri-environment scheme, but the evidence that this led to any significant or sustained changes in peatland condition is weak at best, and these areas cannot therefore be considered to have been 'restored'. Relative to total peat areas, the largest proportional areas of reported peatland re-wetting have been in England and Wales. These activities have mainly occurred on upland bog, although some re-wetting of cropland and intensive grassland has also taken place. In addition, there were small net reductions in the extent of forestry on peat in England and Wales from 1990 to 2013, but in Scotland and Northern Ireland (and despite large recent forest-to-bog restoration projects, particularly in Scotland's Flow Country) there were net increases, leading to an overall increase in UK peat under forestry of 24,000 ha during this period. There have been reductions in the extent of industrial peat extraction, of around 7,900 ha, most of which has been in Northern Ireland and England. Since 2013, there has been a step change in the rate of restoration management in Scotland. Under the Scottish Government's Peatland Action funding, a further total of ca. 19,000 ha has been restored between 2013-2019 in Scotland. There are additional projects out with Peatland Action, but we were not able to locate data on their extent. There have also been further projects in Wales, England and Northern Ireland, but it has not been possible to compile these data for this report. Data on restoration activities in the UK's Crown Dependencies and Overseas Territories are generally lacking, but the areas involved are thought to be small. In the Falklands, around 60 ha of peatland have been restored or protected in the last five years (2014-2019), and work to increase this area by Falklands Conservation, the Antarctic Research Trust, and private landowners is ongoing.

It is important to emphasise that current knowledge of both the extent and effectiveness of UK peatland restoration activities is incomplete. The assessment of restoration activities described above was heavily reliant on information provided by individual projects, which did not follow consistent reporting protocols, was rarely spatially explicit, and was almost entirely based on reporting of actions (e.g. km of ditches blocked) rather than measured outcomes (e.g. ha of peat over which water tables were raised compared against unrestored controls). Furthermore, very substantial peat restoration has occurred in the five years since 2013 via funding mechanisms such as the Scottish Government's Peatland Action Fund, Welsh Sustainable Management Scheme and a number of major EU LIFE programmes. More recent grant schemes including the Defra Peat Restoration Fund will deliver additional peat restoration within the next few years. At present the lack of a consistent, objective approach to reporting or quantifying restoration outcomes, together with the absence of a robust satellite-based procedure for monitoring peat condition change, severely limits our capacity to report on the extent, effectiveness or therefore the overall benefits (such as GHG emissions reductions, amongst other ecosystem services) of peat restoration activities supported by these substantial and continuing investments.

Restoration goals and gaps

Restoration goals vary, from mitigating losses of carbon to a desire to full ecosystem restoration to as natural a state as possible. Consequently, there are no standard targets or standard methodologies to assess effectiveness. There is also currently no agreed method on how to report on the extent of the restored area and this needs to be clarified for national reporting in future. There is high resistance to restoring areas of forestry on peat even when these are uneconomic; and despite efforts to have trees' in the right places', there have been cases of a direct policy conflict of the peatland restoration targets and the woodland planting targets. Agriculturally-used peatlands are often seen as not being candidates for restoration as the the income foregone is considered too high in relation to the value of the potential payments for ecosystem services in a restored state. This needs to be further clarified (e.g. hidden subsidies such as pumping costs), however in the interim, measures to at least reduce emissions from agricultural peatlands through altered water management should be explored. Grouse moors often present similar economic issues when assessed for restoration potential. Restoration goals can also get confused in that some habitats on deep peat are designated for the degraded habitat that now exist on top of the soils.

The vast majority of monitoring efforts address hydrological functioning or vegetation composition as indicators of success. There are only a small handful of reports on the recovery of terrestrial and aquatic fauna to date, a major data gap amongst global efforts to improve species monitoring. There is now a significant body of evidence that shows mostly beneficial impacts of peatland restoration. Where negative effects were observed, these were generally transient (disturbance) effects. However, if there is potentially a short-term negative effect on an ecosystem service, this can reduce the willingness of stakeholders to invest in projects which aim to protect the landscape in the longer term. Very few studies to date have reported the longer-term trajectory of restoration efforts, in many cases this is in part due to the limited duration of the restoration funding and compounded further by due to the short-term nature of funding for research and monitoring. The costs of peatland restoration are often not reported and hence there is still a relative lack of data, reducing the opportunity to assess cost effectiveness. Monitoring costs are generally not included in restoration funding, and therefore this lack of funding for research and monitoring is further hampering efforts to understand the potential benefits of restoration. Finally, the effect of nitrogen pollution and climatic change on the future success of peatland restoration remains to be examined. Wildfire incidence appear to be increasing in UK peatlands. Such fires not only destroy any carbon benefit accrued in the vegetation (and sometimes in deeper peat layers), but it is also unknown whether there are any longer-term impacts of wildfire that may adversely affect the condition of the UKs peatlands as a whole or limit the success of peatland restoration effort.

Recommendations

- A major obstacle in measuring success is the lack of a common definition of a target state, and the lack of a common framework for monitoring and reporting. In terms of vegetation monitoring, the Common Standards Monitoring framework is the only common standard that can be applied at present, however it is generally only used for designated site monitoring. It does, however, use a standardised method to score degradation factors as part of the wider site condition assessment methodology. This lack of a common framework requires to be addressed.
- Currently there is no monitoring framework in place in relation to international obligations regarding restoration (Aichi 15) targets or the UK's obligations to report GHG emissions under the UNFCCC and Kyoto Protocol. Biodiversity and wider condition monitoring are still limited to only having a framework for monitoring for designated areas, but reporting intervals are limited and are consistently being missed. There is therefore still no robust estimate of how much of the UK peatland resource is in good condition, poor condition, and/or deteriorating due to climate change. A wider UK peatland monitoring framework, that dovetails with international procedures and requirements should address these critical issues.
- Reporting on extent of 'restored' peatland. Methodologies to prove the extent of successful rewetting need to be developed to ensure a common (and possibly mandatory, in the case of publicly funded projects) future reporting protocol can be developed for national level reporting. Collation of these data may require a decision on an appropriate centralised body at UK or Devolved Administration level for data handling.
- Cost of peatland restoration needs to be reported better, using standardised methods. A better estimate of the cost of restoration in the light of the recommended targets by the Committee on Climate Change would enable better projections of overall cost and thereby allow better alignment of future policy instruments.
- Consider mapping benefits to multiple ecosystem services even if these cannot yet be fully quantified or monetarised. A common scalar could be developed for the systematic assessment of the various potential ecosystem service impacts and this would enable a critical comparison of inter-site restoration success.
- Raise the profile of the (substantive) peatlands in the UK's Crown Dependencies and Overseas Territories and support their work to better describe and understand their ecology, processes, threats and practical restoration.
- Restoration grant aid should fund a level of on-site monitoring appropriate to the uncertainty of the outcome. Monitoring should take place in the restoration area and also in a comparable reference site in the same region, that represents a suitable target state for the restoration site. Reference sites do not need to be fully 'natural' or 'pristine' but could be (for example) intact designated nearby peatland sites at similar altitude and slope, assessed as being in good condition under statutory condition assessments. Reference sites should not contain any unrestored impacts (e.g. unblocked drains). This ground monitoring should be complemented by collating remote sensed indicators of vegetation and moisture conditions from the same sites for the monitoring years. Monitoring funding should be maintained long-term so that periodic (e.g. every few years), updated assessments can be made over many years, gradually building knowledge on long term responses of peatland sites to restoration management, as compared to suitable reference sites.
- Future policy development in Climate Change, Biodiversity, Planning and Agricultural arenas, especially post the (currently still ongoing) Brexit process, should explicitly regard the specific need of peatland restoration and conservation goals, given their importance for greenhouse gas emissions mitigation and in delivering UN Sustainable Development Goal 15.

Main Report

Contents

Background

To complement the IUCN Commission of Inquiry Update, there is a need to refresh the information presented in the Commission of Inquiry on Peatlands (2011)[3] in relation to the State of UK Peatlands. Advances have been made in the use of remote sensing and mapping of peatlands for both national assessment and project specific monitoring. This update specifically includes new information on the peatland restoration and conservation activity that has taken place since 2011, as well as capturing proposed peatland restoration going forward under new funding announcements (e.g. LIFE, agri-environment funding) and new, UK component country-level, peatland actions plans such as those in Scotland and England.

This report seeks to provide updates on the following key issues:

- Outlining our understanding of peatland trajectories from a degraded > restoring > restored state, and the external influences, such as land management practices, which may influence the path or direction of the restoration trajectory
- Briefly summarising the range of techniques being employed to map the peatland resource and condition of peatlands in the UK and UKOTs. Include an overview of current remote sensing projects and the types of peatland data these will generate
- Summarising the extent of restoration activity that has taken place across the UK (inc. UKOTs) since the last assessment report in 2011. Include detail (where available) on:
    - The type of peatland restoration undertaken, and areas restored
    - The techniques used to restore the peatland
    - Management requirements post-restoration
    - Restoration costs (per ha averages)
- Summarising the scale of future peatland restoration that is committed to under existing funding/project agreements across Government, statutory bodies, NGOs and private landowners (where known). Indicate the delivery mechanism for this restoration and its funding source.

Updates on mapping peat soil extent

United Kingdom

There have been a number of additional efforts to map the extent of peat soils in the UK since the 2011 report (Table 1). Most of these efforts have focused on Scotland, where the previous peat soil maps were largely derived from low resolution field surveys. These had resulted in a map output where peat deposits in areas where these occur in mixed soil landscapes were attributed to an estimated proportion for a given area (Chapman et al, 2009[4]). Although it is possible to use this map to calculate an estimated extent of peat soil as per the 2011 State of the UK Peatlands report, there were many uncertainties with this approach as the proportion of peat in each area is estimated on the basis of average statistics from soil series classifications within the National Soils Inventory for Scotland. Work carried out by Scottish Natural Heritage subsequently improved this mapping effort by including habitat (land cover) characteristics and higher resolution maps from the Soil Survey of Scotland (1:25,000) to produce a map output that classified the peat extent into classes of different likelihood categories to be priority habitats and/or containing high levels of soil carbon. The BEIS Inventory project (2015-2017)[5] then attempted to alleviate the limitations of the Chapman et al (2009) mapping efforts by adding data sources from the British Geological Survey Digimap (v6) and higher resolution maps from the Soil Survey of Scotland (1:25,000), applying a majority rule criterion for

[3] Joint Nature Conservation Committee, 2011. Towards an assessment of the state of UK Peatlands, JNCC report No. 445.
[4] Chapman, S.J.; Bell, J.S.; Donnelly, D.; Lilly, A. (2009) Carbon stocks in Scottish peatlands., Soil Use and Management, 25, 105-112.
[5] Evans, C., Artz, R., Moxley, J., Smyth, M.-A., Taylor, E., Archer, N., Burden, A., Williamson, J., Donnelly, D., Thomson, A., Buys, G., Malcolm, H., Wilson, D., Renou-Wilson, F. (2017). Implementation of an emission inventory for UK peatlands. Report to the Department for Business, Energy and Industrial Strategy, Centre for Ecology and Hydrology, Bangor.88.pp. Available at: http://naei.beis.gov.uk/reports/reports?section_id=3.

peat-only areas. The extent of peat in mixed soil polygons was spatially limiting to the areas with slopes of less than 15%. This resulted in a model of peat soil extent that was spatially explicit and was verified against National Soil Inventory of Scotland point location data (Figure 1; Artz et al., 2019[6]). Further improvements on the 2011 map were also made by Aitkenhead (2016)[7] utilising Landsat8 data to produce a spatially discrete peat extent model for Scotland. Ongoing work is seeking to validate this model further using the peat depth database compiled from applications to the Peatland Action funding calls (see below). Although the Aitkenhead model[7] output is a 100 m raster, which therefore may overestimate the size of small peat soil deposits or the margins of larger contiguous areas, it is at present the first digital soil model that does not solely rely on the Soils of Scotland survey data. A comparison of the mapped areas of peat extent in Scotland from the Aitkenhead (2016) modelling effort and the map produced for the UK Department for Business, Energy & Industrial Strategy (BEIS) project on Implementation of an emission inventory for UK peatlands (hereafter called the BEIS Inventory project) is shown in Figure 2. More recently, Poggio et al (2019)[8] investigated the combined power of modelling peat extent in Scotland with radar and optical satellite data sources.

The peat extent for England has not been revised since the 2011 report (Table 1). Although very slightly different area figures are shown in the Table 1, these are likely due to minor projection issues. As stated previously, these data were obtained from the attributes for peaty soils from data originating from the British Geological Survey and the National Soils Resources Institute (Cranfield University), and as compiled in the DiGMapGB (Digital Geological Map of Great Britain) Version 7.22 (British Geological Survey) database.

For Wales, the BEIS Inventory project reported 20,000 ha more than stated in the 2011 report (Table 1). The 2011 report used the data from the ECOSSE report (Scottish Executive, 2007)[9], whereas the UK BEIS Inventory project obtained the data generated by the Glastir Monitoring and Evaluation Programme (GMEP) which compiled a new unified peat map for Wales (Evans et al., 2015)[10]. These contained data from the British Geological Survey, Forestry Commission, and Natural Resources Wales.

For Northern Ireland, the 2011 report used data from the Soils Map of Northern Ireland (Cruickshank 1997)[11] to report on peat extent. Subsequent GIS intersections to generate land cover data on peat included the Northern Ireland Peat Survey data (NIPS, Cruickshank and Tomlinson, 1988[12]). The UK BEIS Inventory project initially used a new peat basemap for Northern Ireland based on the BGS 1:10,000 superficial geology dataset, with gaps in coverage 'infilled' with mapped histosol polygons from the AgriFood and Biosciences Institute (AFBI) soil survey 1:25,000 scale. The NIPS land cover data source was also used for the BEIS Inventory report, however it also seemed to indicate that there are further peat deposits in addition to those mapped in the BGS/AFBI database. The BEIS Inventory project report therefore did include these additional areas as they were largely surrounding existing BGS/AFBI peat polygons. This, however, increases the potential area of peat soil in Northern Ireland by 36 kha (Table 1). Further work would be required to check whether these additional areas are all indeed peat soils, although aerial photography-based checks and inspection of attributes of the original NIPS database does suggest this to be the case for areas that were manually checked. Areas

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[6] Artz et al (2019) The potential for modelling peatland habitat condition in Scotland using long-term MODIS data. https://www.sciencedirect.com/science/article/pii/S0048969718352124?via%3Dihub

[7] Aitkenhead (2016) Mapping peat in Scotland with remote sensing and site characteristics. Europ. J. Soil Sci https://onlinelibrary.wiley.com/doi/pdf/10.1111/ejss.12393

[8] https://www.researchgate.net/publication/332058548_Modelling_the_extent_of_northern_peat_soil_and_its_uncertainty_with_Sentinel_Scotland_as_example_of_highly_cloudy_region

[9] http://nora.nerc.ac.uk/id/eprint/2233/1/Ecosse_published_final_report.pdf

[10] Evans, C., Rawlins, B., Grebby, S., Scholefield, P., Jones, P. (2015). Glastir Monitoring & Evaluation Programme. Mapping the extent and condition of Welsh peat. (Contract reference C147/2010/11), Centre for Ecology and Hydrology, Bangor. https://gmep.wales/resources.

[11] Cruickshank, J.G. 1997. Soil and Environment: Northern Ireland. Agricultural and Environmental Science Division, DANI and The Agricultural and Environmental Science Department, the Queen's University of Belfast.

[12] Cruickshank, M.M. & Tomlinson, R.W. 1988. Northern Ireland Peatland Survey. Unpublished report to the Department of the Environment (Northern Ireland).

that the NIPS attributed as ‘thin’ or ‘rocky’ were excluded as these are more likely to be below the country threshold depth for peat. The BGS dataset defines peat as locations where the depth is more than one metre, and therefore the NIPS dataset may be a legitimate source of data where peat depth is < 1m.

Table 1. Peat areas reported in JNCC (2011) and updated/additional area estimates based on more recent mapping, where available, from the UK BEIS Inventory project (Evans et al., 2017[5]). Note that only true peats (not ‘peaty soils’) as per national definitions are included in the estimates, and that data are not available for separating deep from ‘wasted’ peats in any country other than England. Peat areas in other UK Overseas Territories and Crown Dependencies have not been quantified.

Country/administration	2011 (ha)	Updated (ha)	Change
Scotland	1,726,900	1,947,750	+220,850
England (deep)	495,828	495,828	-
England (wasted)	186,372	186,372	-
Wales	70,600	90,050	+19,450
Northern Ireland	206,400	242,622	+36,222
UK Total	**2,686,100**	**2,962,622**	**+276,522**
Isle of Man	No data	475	+475
Falkland Islands	No data	282,100	+282,100
Combined total	**Not available**	**3,245,197**	**+559,097**

Crown Dependencies (CDs) and Overseas Territories (OTs)

Peat extent in the Crown Dependencies (the Channel Islands and Isle of Man) and Overseas Territories has not yet been fully mapped. Within the CD’s, there may be small areas of peatland in the Channel Islands. The only peat map currently available for the Isle of Man is the BGS 1:50,000 superficial geology map, which records a small area (476 ha, Table 1) as peat in lowland areas and it is this figure that was used in the BEIS Inventory project (Table 1). A report by Sayle et al. (1995)[13] suggests that a similar area may be occupied by blanket peat in the uplands, but it is likely that this area did not meet the 1 m depth threshold used in the BGS mapping. Weissert and Disney (2013)[14] estimated a much larger (> 5000 ha) peat area but were unclear with regard to their depth thresholds. These two publications did not provide spatial datasets and therefore only the 476 ha in the lowlands of the Isle of Man were reported in the BEIS Inventory project.

The UK Overseas Territories presently include Anguilla, British Antarctic Territory, Bermuda, British Indian Ocean Territory, British Virgin Islands, Cayman Islands, Falkland Islands, Gibraltar, Montserrat, St Helena and Dependencies (Ascension Island and Tristan da Cunha), Turk and Caicos Islands, Pitcairn Island, South Georgia and South Sandwich Islands, and the Sovereign Base Areas on Cyprus. Some updates on the Caribbean OTs can be found in the 2011 Brief Summary on the state of peatlands in British Overseas Territories and Crown Dependencies[15], which highlighted that there are peat deposits of unquantified extent and condition in Bermuda, Tristan da Cunha, Turks and Caicos Islands and the Caiman Islands; with small areas on Anguilla, the British Virgin Islands and Montserrat. There are currently no digital soil maps of these deposits available (Moxley et al, Date unknown)[16].

[13] Sayle, T., Lamb, J., Colvin, A., Harris, B. (1995) Isle of Man — Ecological Habitat Survey: Phase I (1991–1994) Final Report. Department of Agriculture, Fisheries and Forestry, Isle of Man. Available at: https://www.gov.im/media/60296/daffphaseiecologicalsurveyrepor.pdf

[14] Weissert and Disney (2013) Carbon storage in peatlands: A case study on the Isle of Man. https://www.sciencedirect.com/science/article/pii/S0016706113001262?via%3Dihub

[15] IUCN (2011) OT/OC report of the state of peatlands. Brief summary of the state of peatlands in British Overseas Territories and Crown Dependencies. UK Committee Peatland Programme.

[16] Moxley, J. (unknown date) Organic Soils in the UK Oversas Territories and Crown Dependencies. Peat from Penguins to Palm Trees. Poster presentation at IUCJN UK Peatland Prgramme

Within the South Atlantic OT's, the Falkland Islands have by far the largest peat extent of any of the UK's Overseas Territories, indeed they were previously assumed to be covered entirely in peat in the UK emissions inventory assessment, but figures were not included in the 2011 report. Although not 100% peat covered, the islands nevertheless contain a significant fraction of the UK's total peat area. The Falklands peat base map that was produced for the BEIS Inventory project was derived from a BGS superficial geology map produced as part of a geological survey of the islands by Aldiss and Edwards (1999[17]). Estimates of the peat extent in upland areas were produced using a 15% slope threshold (based on results of a limited field survey), whilst lowland valley bottom areas were assumed to be 100% peat soils. Further mapping work is currently ongoing through a Darwin+ project. Assessment, monitoring and restoration techniques for peatland ecosystems in the Falklands are limited and will often differ significantly from those for the UK and other UK Overseas Territories[18]. In other words, not all of the techniques and measures described below will be appropriate for the Falklands. There are currently no digital soil maps of peatland extent for South Georgia and the South Sandwich Islands or for St Helena and Ascension islands (Moxley et al, Date unknown).

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conference. https://www.iucn-uk-peatlandprogramme.org/sites/www.iucn-uk-peatlandprogramme.org/files/CEH%20-%20Organic%20soils%20in%20the%20UK%20overseas%20territories%20and%20crown%20dependencies.pdf

[17] Aldiss, D.T., Edwards, E.J. (1999). The geology of the Falkland Islands. British Geological Survey Technical Report WC/99/10. British Geological Survey, Keyworth.

[18] Macadam and Upson (date unknown). Peatlands in the Falkland Islands. http://www.iucn-uk-peatlandprogramme.org/sites/www.iucn-uk-peatlandprogramme.org/files/12.06.27.1Peatlands%20in%20the%20Falklands_JMcAdam_0.pdf

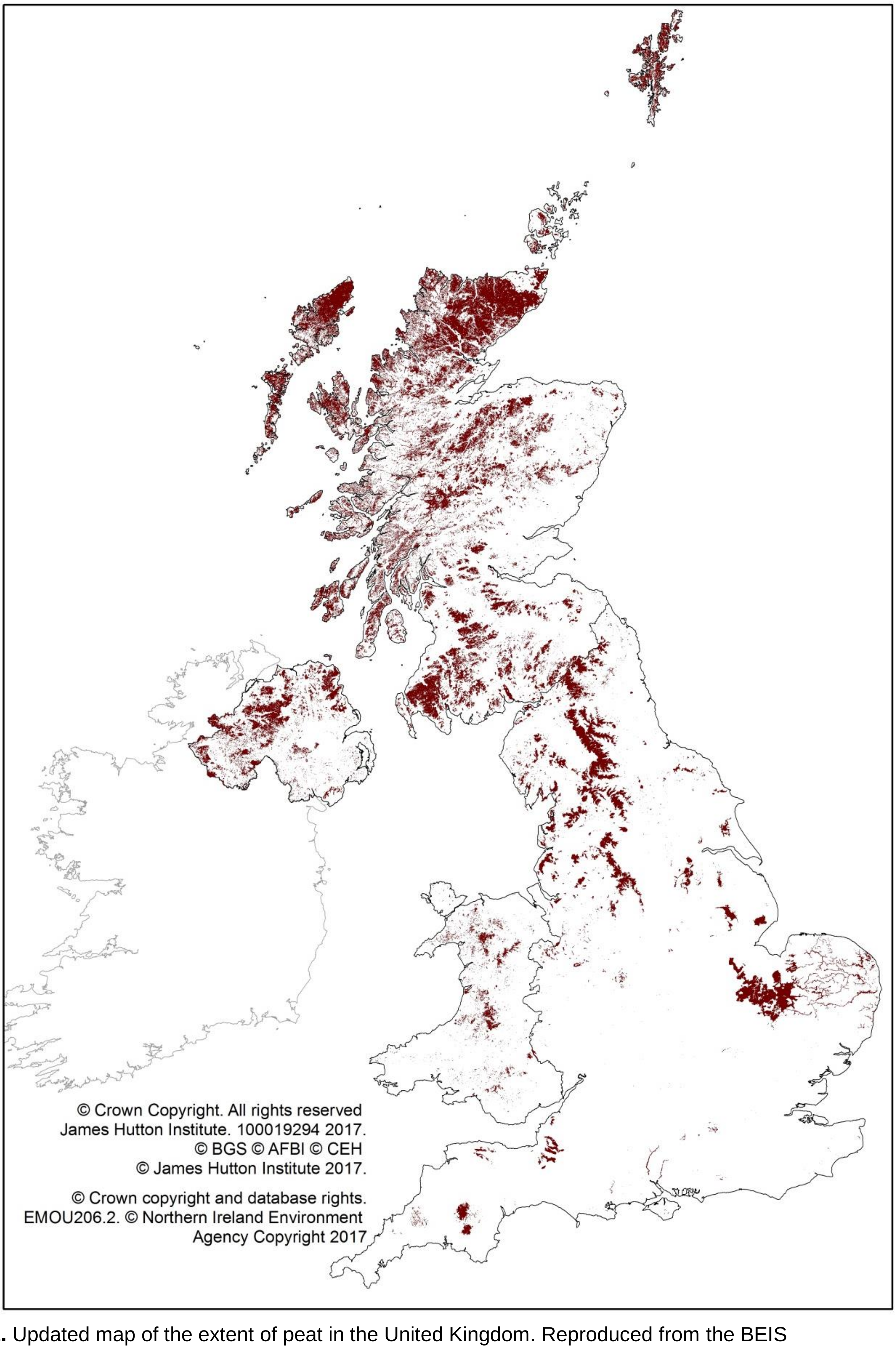

Fig. 1. Updated map of the extent of peat in the United Kingdom. Reproduced from the BEIS Inventory project (Evans et al., 2017[5]), with permission.

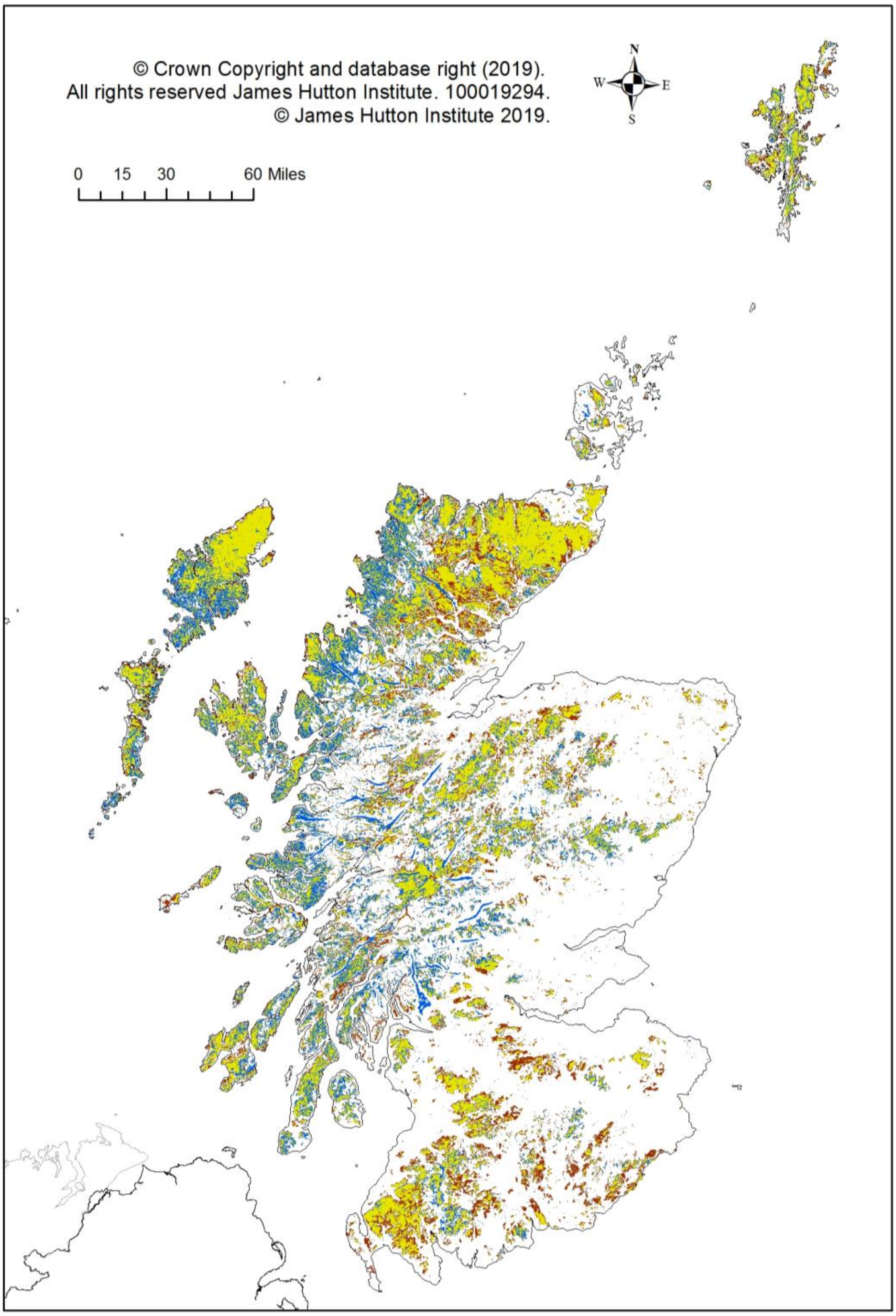

Fig. 2. Comparison of modelled peat extent in Scotland of two approaches (detailed in Aitkenhead (2016)[7] and Artz et al (2019)[6], the latter of which formed the map in the BEIS Inventory project (Evans et al., 2017[5]). Areas where both models predict peat are shown in yellow. The Aitkenhead (2016)[ibid.] model (blue) predicts additional peat coverage in Western Scotland; whereas the BEIS Inventory approach predicted additional peat predominantly around areas of agreement between the two models (brown). Area estimates based on the Aitkenhead (2016) [ibid.] model, however, inflate the total peat extent to a higher value than the BEIS Inventory estimate due to the relatively low resolution (100 m) of the model output. Future ground-truthing efforts should focus on areas of disagreement.

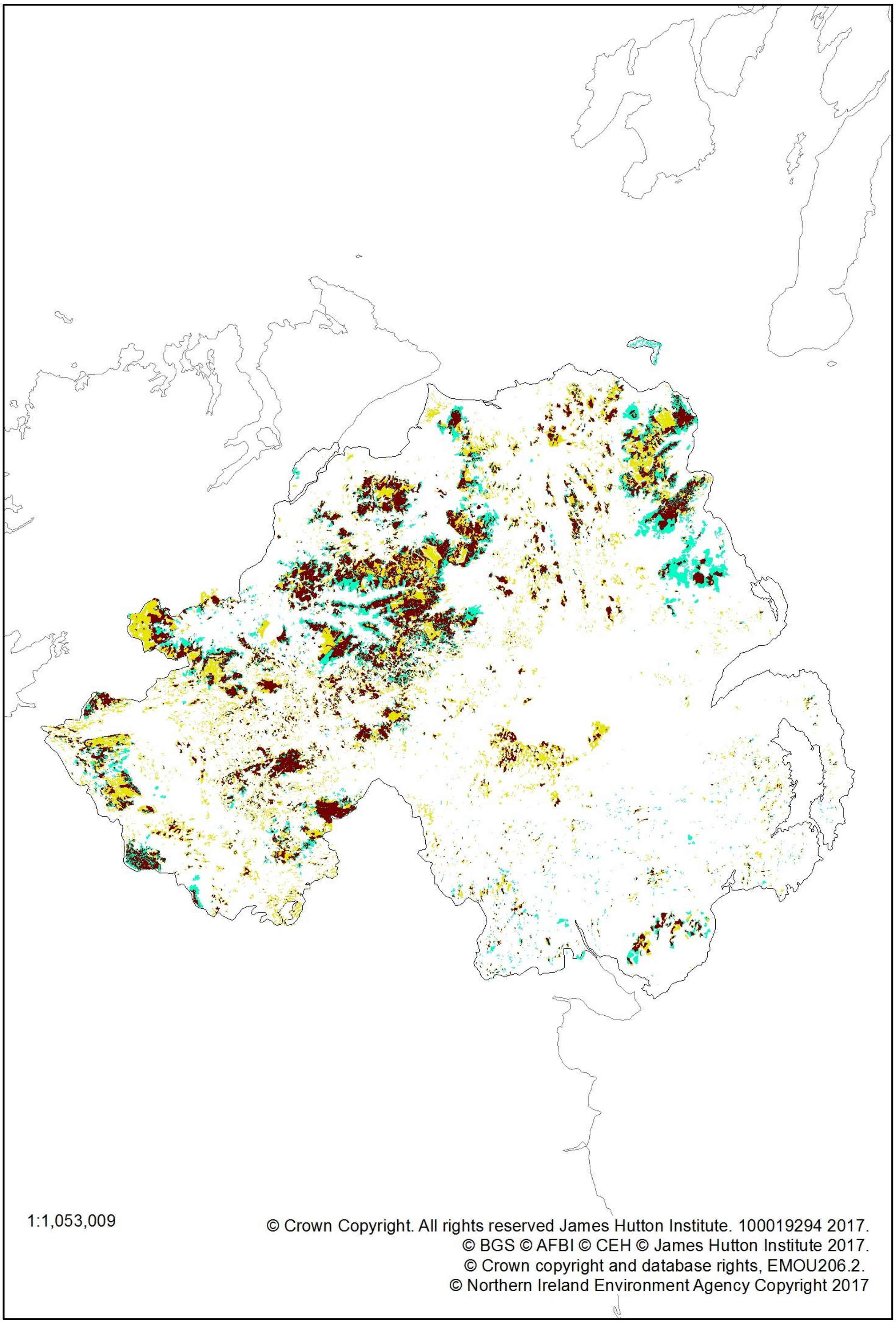

Fig 3. Uncertainties exist over the extent of peat soil in Northern Ireland. There are two datasets that contribute to the full extent by the three colours shown in this figure. Areas in yellow are common to both datasets. Additional areas that only appear in the dataset compiled by the northern Ireland Agri-Food and Biosciences Institute (AFBI) are shown in brown, whilst further additional areas in blue originate from the Northern Ireland Peat Survey (NIPS). Such areas are often described as peat cuttings in the NIPS, so presumably are peat soils. It is possible that these constitute shallower areas than the BGS 1 m threshold for mapping and therefore these were included in Evans et al., 2017[5].

Other advances in mapping peat extent

Peat depth mapping using ground-penetrating radar (GPR) is also beginning to be used across larger areas. Parry et al (2014) assessed the relative accuracy of (hand-held) GPR against manual peat depth probes in a blanket bog catchment and found that GPR may provide more accurate estimates of peat depths, and therefore could also prove more accurate in determining the margins of peat deposits. High resolution airborne gamma ray surveys are also being tested and show potential for the determination of peat extent. Gamma ray surveys return a signal of a specific amplitude from the bedrock underlying the soil, which is then attenuated by soil moisture and the density/porosity of the soil, Peat soils are relatively easily identified due to their high moisture content and low porosity and a number of case studies at a number of UK locations were able to recreate the peat extent of the Digital Geological Map of Great Britain (e.g. Gatis et al., 2019[19]).

Updates on mapping peatland condition

Peatland condition mapping was traditionally achieved through upscaling from field-based surveys, such as the Common Standards Monitoring programme (CSM; JNCC, 2004[20], 2009[21]) protocols on designated sites. The latest UK-wide update on trends in condition on peat forming Priority Habitats was the 2013 Habitats Directive Report[22]. This report suggests that, overall, all nine peatland habitat types under nature designation are currently in bad condition. Six of the peatland habitats were considered to show an overall improving trend in condition status. The majority of improving habitats, however, are fen type habitats, which occupy a relatively small proportion of the total UK peatland area. The condition of most bog habitats, including that of blanket bog, was declining. This is a worse picture than suggested in the previous report published in 2007, and primarily due to changes (improvements) in methodology, but in one instance, for active raised bogs, a genuine decline in trend was identified. For non-designated areas, protocols are not harmonised. Blanket bog areas in England that are managed under an Agri-Environment Schemes (AES) such as Higher Level Stewardship agreements (HLS) are monitored using a system similar to CSM, where each feature has a number of specific condition assessment targets which are used to indicate the initial condition of the habitat. These attributes as defined in the Farm Environment Plan (FEP) Manual (Natural England 2010[23]) are most commonly used to indicate initial condition of habitat features, guiding selection of appropriate objectives and management options during preparation of an HLS agreement[24]. Other data sources are the Countryside Survey (2000) and SSSI/ASSIs (Sites/Areas of Scientific Special Interest) and SACs (Special Areas of Conservation) site surveys on conservation agencies in each country. Whilst data from such schemes are generally comparable if care is taken, there is a lack of national coverage from these datasets which precludes mapping of peatland condition at national scale. Additionally, the location of sites can vary between surveys or, in the case of the Countryside Survey, be confidential, limiting the use of these data for upscaling.

The 2011 IUCN report utilised largely data from the Land Cover Map 2000 or the Land Cover of Scotland 1988 where these were more detailed than in the LCM2000. The LCM2000 does not map

[19] Gatis, N. et al. (2019) Mapping upland peat depth using airborne radiometric and lidar survey data. Geoderma 335: 78-87. https://www.sciencedirect.com/science/article/pii/S0016706118303495
[20] Joint Nature Conservation Committee. (2004) Common Standards Monitoring Guidance for Lowland Wetland. JNCC, Peterborough [online]. Available: http://www.jncc.gov.uk/page-2235
[21] Joint Nature Conservation Committee.(2009) Common Standards Monitoring Guidance for Upland Habitats. JNCC, Peterborough [online]. Available: http://www.jncc.gov.uk/page-2237
[22] http://archive.jncc.gov.uk/page-6387
[23] Higher Level Stewardship: Farm Environment Plan (FEP) Manual (NE264, 2010) https://webarchive.nationalarchives.gov.uk/20150303063952/http://publications.naturalengland.org.uk/publication/32037
[24] Penny Anderson Associates (2014) Improving the Evidence Based Guidance Relating to Favourable Condition for Priority Habitats, SSSIs and SACs: Blanket Bog. Natural England Commissioned Report.

drainage ditches, erosion, rotational burning or peat cutting and therefore additional data were sought from Biodiversity Action Plan (BAP) inventory mapping sources for England (Natural England, 2010[25]) and Wales (Blackstock et al., 2010[26]). Natural England (2012)[27] also commissioned a study of aerial photographs taken during 2002-2007 to map the extent of key visible peatland types within deep peat areas above the Defra "moorland line". This work, when combined with the LCM2000 and other information held by Natural England, resulted in the peat condition figures presented in the 2011 IUCN report. The BEIS Inventory project (Evans et al, 2017[5]) also compiled various national scale land cover datasets to try to produce harmonised peatland condition maps across the UK. For England, the NE257 dataset (Natural England, 2010) was used in conjunction with the Land Cover Map 2007 (LCM2007) and the most up to date information on woodland cover from the National Forest Inventory (2013 data). The results are not compatible as the categories have changed between the different reports, and because the data presented in the 2011 IUCN report included land with overlapping management in each category (i.e. the sum exceeds the total peat extent area). The data from the aerial photography-based mapping for England's peatlands (Natural England, 2012) could not be integrated into the BEIS mapping work as there was incomplete coverage across England's peat soils. A more recent mapping effort of the forestry resource on peat soil in England was produced by Forest Research (2014)[28] which also includes decision support material for whether restoration should be considered.

For Scotland, the 2011 IUCN report did not include figures on areal extent of land cover on peat, but referred to the Land Cover of Scotland (1988) classification as the primary data source available. The BEIS report (Evans et al, 2017[5]) also used this dataset, but information was augmented where more recent information was available, for example on forestry on peat via 2013 National Forest Inventory data, on active peat extraction from CEH LULUCF datasets, on drainage from recent estimates from Artz et al (2017)[29] and on the area of bare peat within eroded areas on the basis of a limited aerial photography assessment completed within the project. Therefore, the BEIS Inventory report presents a more up to date, although still incomplete, picture of Scotland's peatland condition.

For Wales, the 2011 IUCN report did not report broken down figures for different condition categories due to a mismatch of areal extent between the peat soil mapping in the ECOSSE project and the habitat mapping data from the Phase 1 Habitat Survey of Wales (Blackstock et al., 2010)[21], although a map of the condition classes from the Phase 1 Habitat survey was provided. The BEIS Inventory project used the same Phase 1 Habitat survey data in a GIS intersection with the new unified peat map (which was partly based on Phase 1 data), which resolved this former areal mismatch. The only figures that can be compared between the reports are the areas of unmodified (near-natural) land in the two reports, which are 24,000 ha in the JNCC 2011 report and 23,548 ha in Evans et al (2017[5]).

For Northern Ireland, as for Wales, the 2011 IUCN report did not report broken down figures for different habitat classes but did include a map of condition classes based on the Northern Ireland Peatland Survey (NIPS, Cruickshank and Tomlinson, 1988[10]) and the Landcover Map 2000 (CEH, 2002)). The BEIS Inventory report updated this using information from the LCM2007 instead of the LCM2000 and used the combined peat extent map as discussed earlier. The BEIS Inventory project updated this using information from the LCM2007 and the National Forest Inventory (2013).

Data on condition categories for the OTs/CDs were largely missing or relied on the LCM2000.

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[25] Natural England. (2010) England's peatlands: Carbon storage and greenhouse gases. Report NE 257, Natural England, Sheffield. ISBN 978-1-84754-208-3 [online]. Available from: http://publications.naturalengland.org.uk/publication/30021 .

[26] Blackstock, T.H., Howe, E.A., Stevens, J.P., Burrows, C.R. and Jones, P.S. 2010. Habitats of Wales: a comprehensive field survey, 1979-1997. University of Wales Press, Cardiff. 229 pp.

[27] Natural England (2012) Mapping the status of upland peat using aerial photographs http://publications.naturalengland.org.uk/publication/369581

[28] Anderson et al (2014) An assessment of the afforested peatland in England and opportunities for Restoration. https://www.forestresearch.gov.uk/tools-and-resources/peatland-restoration/

[29] Artz et al (2017) Comparison of remote sensing approaches for detection of peatland drainage in Scotland. https://www.climatexchange.org.uk/media/1483/comparison_of_remote_sensing_approaches_for_detection_of_peatland_drainage_in_scotland.pdf

Overall, the BEIS report data suggested a not dissimilar picture to the narrative in the UK Commission of Inquiry report (2011). Forestry conversions on peat occupy around 18% of the UK's peatlands. Agricultural conversion affects around 7% of the peatland, with much of the cropped areas and intensive grassland on so called 'wasted' peat (Figure 4). Wasted peat are former peatland areas that have been so degraded that their depth no longer meets the minimum depth definition but which in many cases still retain an upper layer of peat soil and may therefore produce emissions approaching those from deeper peatlands. Around 40% of the peatlands has been modified through erosion or conversion to a more grass- or heather-dominated vegetation, around 8% is converted to grassland, and just under 5% has been used for peat extraction for domestic or horticultural use. Only around 23% remains in a near-natural state. However, it is critical to acknowledge the reports caveats that these estimates are not very robust, due to the assumptions that had to be made in order to compare land cover across different mapping sources. These may cause classification errors and a recommendation was therefore made to improve the mapping of peatland condition using a harmonised UK protocol.

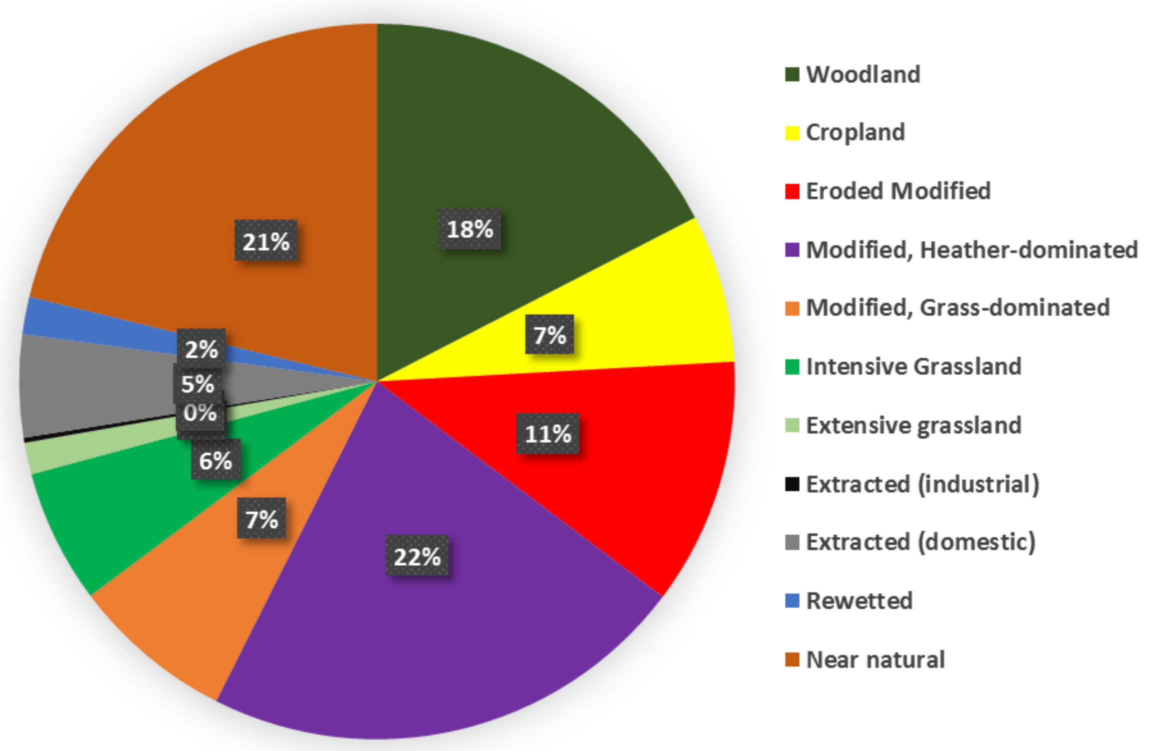

Fig. 4. Best estimate of current distribution of condition of peatlands (UK average, from Evans et al., 2017[5]) Rewetting data from best estimate until 2013.

Even with the latest effort to map condition across the UK peatlands, a significant number of challenges were encountered. As is evident from the list of data sources mentioned above, there is no single spatial dataset currently available that captures all of the required information to calculate up to date figures for the extent of peatlands in different condition classes. Several of the data sources on habitat classification are only updated at irregular intervals (e.g. LCM), whereas others are much more up to date (e.g. National Forest Inventory). This can cause discrepancies such as sizeable areas in the latest Land Cover Map (2015) still being classified as forestry when they were felled for restoration some time previously. There were also a number of important data gaps, notably in the locations of drained peatlands in Scotland (see also below) and data on the spatial extent of rewetting (also further detailed below). There remains an urgent need for a harmonised monitoring framework across the whole of the UK that encompasses both designated and non-designated sites. Due to the large land area involved, it is highly likely that remotely sensed data sources are required to be included in such efforts. Clutterbuck et al (2018)[30] discussed some of the potential of these methods in a recent book chapter.

Use of aerial photography and LiDAR

Remote sensing can take various forms, ranging from aerial photography to the various satellite data sources available at present. Lees et al (2018)[31] summarised these various techniques for use on peatlands in the context of monitoring carbon emissions but the same tools can be applied to map condition (and often condition is used as a proxy for emissions). Resolution of aerial photography can range between <2 cm^2 to 1 m^2, depending on the type of aircraft used (drones, planes, helicopters), the height at which the aircraft flies and the resolution of the camera/sensor employed. Typically, aerial photography data sources have been limited to visible optical and near infrared band measurements, however multispectral sensors that are light enough to mount to small aircraft including drones are now becoming more widely available that expand the range to thermal infrared and into the microwave spectrum. Visible/Near infrared data can be used to produce various indices of the 'greenness' of vegetation, whilst thermal infrared measurements can be used to infer soil moisture content. Since 2011, a larger variety of aerial photography data sources at national level has become available, and there are now rolling programmes that produce up to annually new images such as GetMapping which are now free to use for qualifying local government[32]. Microwave imaging produces a backscatter image, which can also be used to model land cover, vegetation structure and soil moisture content. At slightly lower resolution, the laser-based Light Detection and Ranging (LiDAR) method detects topography and can therefore be useful in monitoring vegetation change. Traditionally used to monitor canopy height in e.g. forestry plantations, it can also detect changes in topographical 'texture' after restoration practices, e.g. the infilling of drains, erosion gullies or planting furrows, if measurements have been carried out at the appropriate resolution.

Various projects such as the Glastir Monitoring and Evaluation Programme for Wales (2015)[33] have used aerial photography, on its own or in conjunction with satellite data, to map peatland condition. Natural England commissioned a report that mapped peatland condition across England, primarily to fill a data gap in the upland areas[25]. Locally, peatland partnerships and NGOs (e.g. RSPB) are increasingly moving towards drone assessments of peatland condition due to the high resolution of the imagery. RSPB assess bare peat extent in relation to monitoring restoration of eroded areas in a forthcoming work on high altitude bogs at Abernethy. There is a related PhD project (Henk Pieter Sterk, UHI) ongoing at present. However, other users of drone-derived data, especially where larger areas require to be assessed, report that imagery is affected by differences in light levels introduced due to the length of time it takes to fly such larger areas (e.g. effects of changing illumination through time), which then affects subsequent vegetation classification. This then necessitates a lot of ground truthing in the area and hence increases overall cost. The Peatland Action team obtained high resolution visible and NIR imagery for 15 restoration sites before work began, and regularly use e.g. GetMapping imagery to map drains and erosion features prior to restoration. It is the intention that these data will become publicly available. A ClimateXChange Scotland project was aimed at detecting drainage in Scottish peatland using a combination of manual detection based on spatial sampling of 500 m blocks of aerial photography using a Latin hypercube spatial sampling approach and attempted to model drainage using satellite data sources (Aitkenhead et al., 2016[34]; Artz et al., 2017[35]). The

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[30] Clutterbuck et al (2018) The potential of geospatial technology for monitoring peatland environments. http://irep.ntu.ac.uk/id/eprint/32921/
[31] Lees et al (2018) Potential for using remote sensing to estimate carbon fluxes across northern peatlands – A review. https://www.sciencedirect.com/science/article/pii/S0048969717324464
[32] https://www.getmapping.com/news/2019/03/getmapping-and-bluesky-launch-online-aerial-mapping-service-public-sector
[33] Emmett et al (2017) http://nora.nerc.ac.uk/id/eprint/518194/1/N518194CR.pdf
[34] Aitkenhead et al. (2016) https://www.climatexchange.org.uk/media/1489/detection_of_peatland_drainage_with_remote_sensing__a_scoping_study.pdf
[35] Artz et al. (2017) https://www.climatexchange.org.uk/media/1483/comparison_of_remote_sensing_approaches_for_detection_of_peatland_drainage_in_scotland.pdf

sampling of the manually mapped drainage was sufficient to determine a reasonably robust estimate of the percent of drainage in Scotlands' peatlands, however the satellite data-based modelling of drainage was unsuccessful. Drainage channels can often be obscured by overhanging dwarf shrubs, making it sometimes difficult to detect old drains on aerial imagery. A recent PhD studentship (E. Cole)[36] developed the use of very high resolution hyperspectral aerial imagery to study restoration effects at sites spanning an age gradient of four years on the Bleaklow plateau and nearby Blackhill in the Peak District National Park.

Satellite data-based condition assessments

Satellite data sources range in spectral and spatial resolution, overpass frequency and time since data became available, There is now much more choice of freely available satellite data sources than was the case in 2011, specifically with the launch of the Sentinel-1 and 2 series of satellites, which produce radar and optical data, respectively, at better resolution and higher frequency than some of the longer-running satellite programmes such as Landsat and MODIS. Commercially available imagery such as Worldview produces potentially high spatial resolution data but has not been widely used in the scientific community due to the purchase cost.

The recently completed Defra pilot project[37] used Sentinel-2 optical and Sentinel-1 synthetic aperture radar (SAR) data to test a peatland condition classification scheme in 5 peatland areas of 100 km^2 across the UK. This project used the classification developed for the BEIS Inventory project and tested a supervised classification method to detect these classes, using ground observations to develop the models. The project showed encouraging results for the detection of the majority of the peatland condition classes in the five UK test, although confidence for some of the semi-natural condition classes was relatively low, in part due to the lack of appropriate ground observations. Ground observations that match the resolution of the satellite data sources are relatively rare. Most vegetation or habitat condition surveys are performed on plots of $< 4\ m^2$, sometimes in conjunction with line of sights indicators, and using such data without additional checks may erroneously assume that the remaining proportion of the corresponding satellite pixel is covered with peatland in the same condition. Additionally, such surveys often include elements that a satellite signal would not be able to detect (e.g. "understorey" moss and liverwort species, or indicators of browsing). A very common issue is lack of appropriate sampling effort across all of the desired condition categories, or indeed, insufficient spatiotemporal coverage. Finally, ground observation data that are georeferenced with handheld GPS systems have a location error margin of several metres. Notwithstanding these limitations, Williamson et al (2019)[37] were able to produce reasonable models of peatland condition for categories where good ground observations were in existence.

The Glastir Monitoring and Evaluation Programme for Wales (2015)[29] evaluated net primary productivity mapping from Landsat 5 data within Wales and produced a woody cover product from a combination of airborne radar and optical satellite data, combined with data from the National Forest Inventory.

Natural England have been running a pilot project with Manchester University on using Sentinel-2 data on the Bowland Fells to look at blanket bog condition.

Recent work at University of Reading and James Hutton Institute via a PhD studentship (K.Lees)[38] developed a model using MODIS satellite data to assess the gross primary productivity in restored peatland sites in the Flow Country, Scotland, and this suggested that the photosynthetic fixation potential of formerly afforested peatlands could be restored as soon as 5-10 years after restoration

[36] Elizabeth Cole PhD (2012). https://www.research.manchester.ac.uk/portal/files/54528488/FULL_TEXT.PDF
[37] Williamson et al (2019) The role of earth observation in an integrated framework for assessing peatland habitat condition and its impact on greenhouse gas accounting. Not yet publicly available.
[38] Lees et al (2019) A model of gross primary productivity based on satellite data suggests formerly afforested peatlands undergoing restoration regain full photosynthesis capacity after five to ten years. Journal of Environmental Management 246,594-604. https://www.sciencedirect.com/science/article/pii/S0301479719303421

management.. MODIS satellite data were also used recently to model peatland condition across Scotland as per the Common Standards Monitoring assessment (Artz et al., 2019[6]).

Some of the most recent developments include the use of interferometry synthetic aperture radar (inSAR) to assess peatland condition via surface motion monitoring (Alshammari et al, 2018[39]). This method measures the vertical surface motion characteristics of the peat (bog breathing) and provides data to millimetre resolution of surface movement. Surface motion is determined by how the peat stores and exchanges water, for example, over the course of a year, the surface of peatlands in good condition expands during the summer and contracts in the autumn. Conversely, degraded bog either continuously contracts (due to subsidence and/or oxidation of the peat) or may contract in summer due to soil moisture deficit and re-expand in autumn as the site rewets. Initial results show that the techniques provide a reliable and sensitive means of assessing peatland condition over large areas. A current project funded by the NERC will work with stakeholders to build confidence in the method and develop the technique into a useful and well understood tool.

Finally, Scottish Water commissioned a project through Rezatec[40] that utilised a variety of aerial photography and satellite data sources to map condition indicators in an area covering 18% of its catchments. This is probably the study with the highest spatial coverage that utilises remotely sensed data sources at present. Rezatec also used this methodology to map peatland condition for Northern Ireland Water for its Dungonnell catchment, on the Garron Plateau.

Recommendations for future protocols

Based on the limited additional evidence at national level across all four UK countries, it cannot be stated whether significant changes have occurred. The most recent evidence suggests that not much has changed since the last IUCN State of Peatlands report. The figure for peatland remaining in near-natural condition is still around 20%, but there have been significant additional efforts to restore peatlands since the 2011 report. It is difficult to compare the other, degraded, condition figures as the categories are not straightforward to compare. New approaches to national land cover mapping should explicitly take into account the need to map peatlands that have been subjected to land cover conversion. A harmonised UK peatland mapping effort is required that uses appropriate land cover categorisation suitable for integration with UK emissions reporting. One particular issue, for example, that requires to be addressed, is the development of windfarms on peat soils. To date, there has been no national assessment of the area that has been developed and what the impact of this is, whether in terms of the lost volume of peat for foundations or the effect of access tracks and associated drainage on peatland functioning. On the other hand, many windfarm developments have included habitat restoration on peat, for which area figures are also not yet compiled. The relatively large area of peatland used for intensive grassland or crop production may benefit from assessment of options for better management, e.g. by raising the water table to reduce emissions[41].

JNCC and an inter-agency working group on the future of the Common Standard Monitoring methodology, comprising the four statutory nature conservation bodies (Natural England, Natural Resources Scotland, Scottish Natural Heritage and the Department of Agriculture, Environment and Rural Affairs, Northern Ireland), also made a recommendation that a review of peatland monitoring methods, complete with strengths, weaknesses, opportunities and risks should be requested. They highlight that there is clearly much potential for the use of Earth Observations in peatland condition monitoring, particularly in monitoring vegetation changes, land cover conversion inclusive of restoration, and in future, potentially in the remote assessment of greenhouse gas emissions, As yet, there is no defined protocol for such remote monitoring, and all publications to date stress the crucial

[39] Alshammari et al (2018) Long-Term Peatland Condition Assessment via Surface Motion Monitoring Using the ISBAS DInSAR Technique over the Flow Country, Scotland. https://core.ac.uk/download/pdf/159994108.pdf
[40] https://spaceforsmartergovernment.uk/case-study/rezatec-using-earth-observation-for-efficient-and-effective-peatland-assessment-phase-2/
[41] Evans et al (2016). Lowland peatland systems in England and Wales – evaluating greenhouse gas fluxes and carbon balances. Final report to Defra on Project SP1210, Centre for Ecology and Hydrology, Bangor.

role that adequately collected ground observations in a format compatible with satellite data outputs, play in remote monitoring efforts.

At international level, the Food and Agriculture Organization of the United Nations (FAO) are initiating discussions about improved monitoring of peatlands within the wider Global Peatlands Initiative[42], including a recent workshop in May 2019. The Indonesian Peat Restoration Agency have, in partnership with various other organisations including FAO and UN-DP and UN-OPS, designed a Peatland Restoration Information and Monitoring System (PRIMS[43]) on an online platform, which is a useful example of how a future UK-wide analogue initiative could be structured.

Peatland restoration update

Definition of a restored area

Lunt et al (2010)[44] reviewed the policies, drivers and practices of peatland restoration in the UK. They did not provide a formal definition of a restored area, but their assessment of evidence on restoration success centred on 1) stability and height of the water table, 2) peat stabilisation and/or carbon sequestration and 3) biodiversity in the sense of the Common Standards Monitoring assessment targets. Lindsay et al (2016)[45] compare restoration to a medical process, beginning with stabilisation of the residual peat and raising of the water table, via active repair of the vegetation component and support through the 'healing process' towards a new equilibrium state that is supported by the prevailing environmental conditions, and ideally one that can begin a new cycle of net accumulation of peat. The IMCG[46] produced a schematic classification (Schumann and Joosten, 2008) based on the effects detected within the fauna; vegetation; hydrology, soil hydraulics, peat from and relief and peat deposits (accumulation), however there is no guidance on formal scoring to derive a working (and cross-country compatible) classification. A possible definition of a restored area is that it can carry out all of the expected ecosystem functions of a natural peatland system, and that the fluctuations in these processes are within the same limits through time and space as in a natural system. This definition would allow development of targets for individual components of the suite of ecosystem functions, as long as a reference, natural, state can be identified and system functioning, and limits can be assessed. Table 2 lists the generic ecosystem services and functions of natural peatland ecosystems; however, the magnitude of each component function and its spatiotemporal fluctuations vary with the environmental conditions across which peatlands form. Thus, knowledge of a local reference system state is required, however in some areas land use conversion has been so extensive as to leave only remnants of potential reference sites. It can be questionable whether these remnant reference sites still perform all of their ecosystem services at an optimal level.

Table 2. Core ecosystem services and functions of natural peatlands (adapted from Kimmel and Mander, 2015[47] to include services and functions to other species beyond humans)

Ecosystem services	Core functions
Provisioning: Food	Production of food in the shape of wild plants for foraging or wild/domestic animals for hunting (both human/wider users)
Provisioning: Water	Storage of water for human and other users (e.g. public water supplies, water for wild animals)

[42] https://www.globalpeatlands.org/ and Link to workshop: https://www.globalpeatlands.org/?p=16418
[43] https://brg.go.id/wp-content/uploads/2019/06/WRI-PRIMS-Brochure-v13-AR.pdf
[44] Lunt et al (2010) http://www.iucn-uk-peatlandprogramme.org/sites/www.iucn-uk-peatlandprogramme.org/files/images/Review%20Peatland%20Restoration%2C%20June%202011%20Final.pdf
[45] Lindsay et al (2016) Peatland Restoration. IUCN UK Peatland Committee Briefing Note 11. http://www.iucn-uk-peatlandprogramme.org/sites/www.iucn-uk-peatlandprogramme.org/files/11%20Peatland%20Restoration_FINAL.pdf
[46] Schumann and Joosten (2008) Global Peatland Restoration Manual. http://www.imcg.net/media/download_gallery/books/gprm_01.pdf
[47] Kimmel and Mander (2015) Ecosystem services of peatlands: Implications for restoration. https://journals.sagepub.com/doi/10.1177/0309133310365595.

Ecosystem services	Core functions
Regulating: Climate regulation	Regulation of global, regional and local and microscale climates (e.g. regulation of greenhouse gases and contributing compounds that decompose to greenhouse gases; regulation of climatic processes such as transfer of heat and moisture, aerosol formation, and changes to albedo)
Regulating: Water regulation	Regulation of catchment hydrology (e.g. water storage, recharge and discharge)
Regulating: Water purification and waste treatment	Regulation of hydrochemistry (e.g. retention, removal and recovery of excess nutrients and pollutants)
Regulating: Erosion protection	Regulation of soil condition (protecting peat and, in the case of shallower peat, any underlying soils, from erosion)
Supporting services: Soil formation	Regulation to ensure peat accumulation occurs at its optimal level
Supporting services: Nutrient cycling	Regulation of storage, recycling, processing and acquisition of nutrients to support appropriate complement of species across all the trophic levels
Supporting services: Provisioning of habitat (MA)/Habitats for species (TEEB)	Provision of appropriate conditions to supply adequate habitat for its natural complement of species
Nature (Intrinsic values) IPBES	Provision of appropriate habitat topography/connectivity to provide habitat for appropriate (including protected) species
Cultural services: Recreational and aesthetic	Provision of opportunities for recreation, tourism and appreciation of nature
Cultural services: Spiritual and inspirational	Provision of functions to ensure human wellbeing, inclusive of religious and spiritual needs
Cultural services: Educational	Provision of opportunities for signalisation and cognition functions, e.g. training, research and education of the wider public

Proxies for assessing the state of ecosystem services and functioning in restored peatlands

Some component ecosystem services and functions have been assessed through the use of proxy indicators for the wider system state. This section briefly summarises these proxies against the ecosystem services summarised in Table 2 and describes how reference states for these are commonly set in restoration project monitoring.

There is little information on the food provisioning service of peatlands, but the water regulating and provisioning services have been the subject of a reasonably robust body of research. Although there is no formally agreed definition of what constitutes a successfully restored water table, Lunt et al (2010) refer to a target of a relatively stable near surface (5-10 cm) level, as most published research on near natural peatlands suggest this to be the average annual water level, with low fluctuations (<10 cm) around this mean[48],[49]. However, there are still a number of uncertainties over how long and, in some situations, whether it is even possible, to restore the hydrological function of the acrotelm peat layer. Most recent publications now use a local near-natural site as a reference, or report progress in terms of hydrological improvements where such reference sites are not locally available (see section on Restoration trajectories – current state of knowledge).

There is less consensus on how to define proxies for successful peat stabilisation (Regulating: Erosion control) or indeed carbon sequestration rates (Regulating: Climate regulation) against a target state, as data from control areas are relatively scarce. In 2011, there was no published data on peat stabilisation and carbon sequestration effects post restoration management. There are still relatively few publications that compare the before and after differences on a single site, or against a local reference site in natural condition (see section on Restoration trajectories – current state of knowledge) but the recent BEIS Inventory project compiled available data on published emissions and found statistically different total GHG emissions from near-natural, rewetted, and degraded sites (Evans et al., 2017[5]). Some reports simply show progress towards a target state, which in itself is a measure of partial success, however it can often be difficult to ascertain whether the rate of progress is fast enough to rebuild a functional ecosystem within a reasonable time.

Definition of the target restored state in biodiversity terms is generally limited to either meeting (some of) the criteria for favourable status under the Common Standards Monitoring protocol, which are dominated by vegetation indicators, or evidence of convergence of community composition of various biota towards a target state (see section on Restoration trajectories – current state of knowledge). Generally speaking, the approach of trying to meet favourable status is adopted because local reference sites in near-natural condition are not available. Notable exceptions to this are projects where such local reference sites do exist, and these projects do tend to include other biodiversity indicators including e.g. wetland bird species abundance, invertebrate or microbial community structure (see section on Restoration trajectories – current state of knowledge. Lunt et al (2010) pointed out the lack of published research on the vegetation response to rewetting practices, although they suggested this may be due to the length of time (2-5 years) it takes before vegetation shows a response given that most restoration projects were still relatively recent at that point in time. Ongoing work within Moors for the Future Partnership and Natural England is trying to define a target state for the desired vegetation communities (MFTF, 2016[50] ; Alderson et al., (2019)[51]). RSPB have a published method for tracking recovery in protected sites (Groom, 2015.[52]). In general, most projects with published monitoring results to date either compare the achieved results to Common Standards Monitoring targets (e.g. Pilkington et al., 2015[53]) or, where this is feasible, to a nearby natural control state that is being monitored at the same time (e.g. Hancock et al., 2018)[54].

The other area of inconsistency is in the definition, and thereby, reporting, of the restored area. At present, this definition seems to vary greatly in the literature to date; including the total area in which restoration activities have been carried out at one extreme, solely the area that has been actively managed (e.g. the area of bare peat that has been revegetated, as seen on aerial photographs) at the other extreme end, or an intermediate way of reporting the restored area as that which will have likely

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[48] Armstrong, A., Holden, J., Kay, P., Foulger, M., Gledhill, S., McDonald, A. T., Walker, A. (2009) Drain-blocking techniques on blanket peat: A framework for best practice. Journal of Environmental Management 90: 3512-3519.
[49] Holden, J. (2009) A grip blocking overview. Report for the Environment Agency. Project 30254994.
[50] https://www.moorsforthefuture.org.uk/our-work/our-projects/moorlife2020/moorlife2020-research-and-monitoring/moorlife-2020-trajectories-for-impacts-of-re-vegetation
[51] Alderson et al. (2019) Trajectories of ecosystem change in restored blanket peatlands. Science of The Total Environment, Volume 665, Pages 785-796 https://www.sciencedirect.com/science/article/pii/S0048969719305765
[52] Groom, A (2015). How to track and ensure the recovery of SSSIs to favourable condition: The milestone approach, RSPB [unpublished]
[53] Pilkington M.G. et al. (2015) Restoration of Blanket bogs; flood risk reduction and other ecosystem benefits. Final report of the Making Space for Water project: Moors for the Future Partnership, Edale.
[54] Hancock et al (2018) Vegetation response to restoration management of a blanket bog damaged by drainage and afforestation. https://onlinelibrary.wiley.com/doi/abs/10.1111/avsc.12367

been influenced by the restoration activities. Various reports have used the completion of rewetting activities (length of drain blocked, length of erosion gully blocked/revegetated) as a metric and applied a standard buffer around each of these linear features to derive a standardised methodology to calculate the area rewetted. It is currently largely unknown how wide the standard buffer should be, although there are a handful of publications that have examined the spatial extent of rewetting after peatland restoration practices (e.g. Anderson and Peace, 2017[55], Williamson et al, 2017[56]). An alternative approach, which was evaluated in the Defra-JNCC peatland remote sensing project (Williamson et al., [37], unpublished) is to use vegetation composition as an indirect, but reliably measurable proxy for water table, on the basis that the vegetation community present at a site reflects average wetness. This approach has the advantages that i) it is not necessary to assume a particular re-wetted distance around a ditch, ii) it is based on the outcomes rather than the intervention (and thus should for example differentiate between successful and unsuccessful ditch-blocking activities), and iii) has the potential to be monitored at large scales using airborne or satellite data (whereas mapping active and blocked ditches requires laborious ground-based mapping or manual digitising of aerial photographs). Methods for low-cost, large-scale outcome monitoring of peat restoration activities are currently being developed and tested as part of a Welsh Government Sustainable Management Scheme project. The current lack of a formal definition of what constitutes a successfully restored area can result in discrepancies for formal reporting. This was highlighted, for example, in assessments of the Peatland ACTION programme (Artz and McBride, 2017)[57]).

It is clear that the lack of (consensus on) a definition of the target state of restoration and how the area of restored peatland should be measured is hindering reporting. An agreed, common, working definition (or failing that, a mandated definition at UK level e.g. by JNCC) would be helpful, while recognising that many different formal, ‘perfect’ definitions might each have merit. Participatory approaches could be employed to produce a working set of definitions at UK level.

Restoration effort to date

Lunt et al (2010) pointed to the Peat Compendium as the source of information on peatland restoration extent for the >170 projects collated therein. Sadly, although elements of this resource now reside on the IUCN UK Peatland Programme website[58], the information is clearly incomplete at national level, and hence, eight years on, it is still not possible to provide accurate figures on the total number of restoration projects achieved to date, let alone the extent of successfully restored peatland area (see below). Table 3 shows the restoration efforts that the BEIS Inventory project was able to compile up until 2013. Further efforts as part of this compilation and a follow-up to the original BEIS Inventory project were able to add significant additional figures up to 2019. Some of the figures in Table 3 may have relatively low confidence as some agri-environment scheme figures were included in the BEIS Inventory compilation, although it cannot generally be proven that such schemes delivered active rewetting through drain or gully blocking rather than passive rewetting (though e.g. scrub or tree clearance, reducing evapotranspiration). The figures, and the additional areas restored since 2012/3 under the various large-scale projects initiated more recently, clearly show substantial progress towards the UK Peatland Strategy target of 2 million ha in good condition, under restoration of sustainable management by 2040. It is too early to speculate about whether national targets for 2020 are being reached at this point, as the data compilation is still incomplete and even data compiled so far are of relatively low confidence.

Table 3 Rewetting since 1990 (ha). Data for 1991-2013 reproduced from Evans et al 2017[5] and new data compiled for this report.

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[55] Anderson and Peace (2017) http://mires-and-peat.net/media/map19/map_19_06.pdf
[56] Williamson et al (2017) https://www.sciencedirect.com/science/article/pii/S0301479716309914?via%3Dihub
[57] Artz and McBride (2017) https://www.climatexchange.org.uk/media/1485/cxc_peatland_action_data_uses.pdf
[58] https://www.iucn-uk-peatlandprogramme.org/projects-map/history-peatland-compendium (*History*) and https://www.iucn-uk-peatlandprogramme.org/projects-map (*Map; Last checked 06.09.2019*)

	England	England (wasted peat)	Scotland	Wales	NI	Isle of Man
Rewetted Bog 1991-2013	24,705	265	20,155	4,013	712	No data
Rewetted Fen 1990-2013	17,835	-	1,171	1,544	150	8
Restoration areas 2013-2019	Unknown (see text)	Unknown (see text)	Up to 72,800* (see text)	Unknown (see text)	>2000 (see text)	No data
Rewetted area	>42,540	>265	Up to ~90,000	>5,557	>2862	8

*Peatland Action running total to date, based on area figures in submitted and accepted grant applications to date (incomplete data, not yet quality controlled, hence please treat with caution; see text for further information);

Additional projects completed since 2013

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- ***Northern Ireland:*** Restoration activities in Northern Ireland are delivered by a large number of funders/project partners including DOENI (Peatland Park project); the Mourne Mountains Landscape Partnership; the Dungonnel Reservoir Interreg project and various Wildlife Trusts. The National Trust also runs a range of restoration projects at the Argory, Co Armagh; on Divis Mountain (near Belfast) and Slieve Donard in Co Down; and a coastal peatland at Fair Head, Co Antrim. Some projects such as the NI Wildfire Stakeholders group, the INTERREG V programme[59], the SCAMP project at the Garron Plateau[60],[61] and HLF projects through Lough Neagh Landscape Partnership Scheme and Heart of Ancient Ulster Landscape Partnership Scheme contain peatland components. Further work will have been carried out as part of the Rural Development Programme (2014-2020), Environmental Farming Scheme (2017-2020) and DAERA NIEA Environment Fund (2016-present), however we were unable to access the figures on area restored under these schemes, or indeed what types of restoration activities have been carried out.

- ***Scotland:*** With significant increases in available funding for peatland restoration since 2012, Peatland Action (SNH) as the organisation responsible for delivering the Scottish Government commitments to restoration has completed ~250 completed restoration projects since 2012 (until December 2018). Of these, some of the 150 projects completed until 2017 were recently estimated at comprising 10,315 ha of area that have been set 'on the road to recovery' (Artz and McBride, 2017[35], SNH Peatland Action website[62]). The Peatland Action programme includes a dedicated data team, which compile data on the location and types of restoration activities undertaken in each situation. Of particular note is that the Peatland Action programme do not used the term 'restored; and rather refer to the achieved state as 'on the road to recovery' (in some ways analogous to the 'unfavourable, recovering' terminology used in Common Standards Monitoring).' Currently, the estimated total area that has been rewetted under Peatland Action projects due completion before March 2019 is around 72,800 ha, however these data are based on the submitted proposals rather than the area actually achieved and furthermore these data have not been fully assessed for quality (SNH, pers. Comm). The compilation of the area restored for this portfolio of projects is still ongoing as there are a number of projects where there have been repeat efforts in neighbouring or indeed identical areas (e,g. initial felling of forestry on peat later followed by blocking up of the

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[59] https://www.ulsterwildlife.org/news/2018/06/25/%E2%82%AC83m-boost-protect-precious-peatlands-and-wetlands-ireland-and-scotland
[60] http://www.iucn-uk-peatlandprogramme.org/sites/www.iucn-uk-peatlandprogramme.org/files/PeatlandUpdateNorthernIreland_MBradley.pdf
[61] https://www.climatenorthernireland.org.uk/cmsfiles/ClimateNI_RSPBFINAL.pdf
[62] https://www.nature.scot/climate-change/taking-action/peatland-action/peatland-action-what-we-do

plough furrows and/or surface levelling). Equally, a number of the earlier projects have not yet been assessed for the area that has been rewetted. Therefore, this figure needs to be considered with extreme caution at present. Other, smaller scale, projects have been delivered through co-funding with the Peatland Code, Scottish Water, SEPA, Heritage Lottery, the National Trust for Scotland (although these were often financed via Peatland Action), EU Life+ projects and volunteer efforts. A further effort on Islay was financed via INTERREG V[63].

- ***England:*** Restoration efforts in England have also stepped up significantly as funding for restoration has increased, for the most part through various different funding streams, including Defra's £10 million capital funding (2017), but especially the EU LIFE fund. These were often only possible by the Water companies and Heritage Lottery Fund putting up match funding to achieve far greater results. The significance of the water companies input, for example, has made possible, for example the SCAMP and SCAMP2 projects[64]. The Yorkshire Peat Partnership aimed to restore 42,500 ha by 2017. The partnership website doesn't give an area completed so far but lists a rather impressive number of completed peat dams, areas with vegetation re-planting, sediment traps and heather bale and stone dams[65]. The Moors for the Future Partnership ran the MoorLIFE project (2010-2015), which included 2,500 ha of blanket bog in the Peak District and South Pennines. The Making Space for Water project delivered 84 ha of upland eroded peatland restoration, monitoring and evaluation on the Kinder Scout plateau, Peak District National Park, between 2009 and 2015 (Pilkington et al., 2015[53]). The MoorLIFE 2020 project (2015-2021) is ongoing and aims to protect the remaining areas of active Blanket Bog within the South Pennine MoorsSAC. The Pennine PeatLIFE project (North Pennines Area of Outstanding Natural Beauty (AONB) Partnership in collaboration with Yorkshire Wildlife Trust and Forest of Bowland) aims to restore 1,300 hectares of bog. The North Pennines Area of Outstanding Natural Beauty (AONB) Peatland Programme[66] has blocked over 1000 km of moorland drains or grips since 2006, have started to restore 320ha of bare peat with the aim of restoring over 580ha. Dove Stone is an ongoing RSPB partnership project with United Utilities, to restore 2,500 ha of blanket bog, in Greater Manchester. Work is also underway at six sites across Greater Manchester, Merseyside and Cheshire through Defra funding[67]. An EU-LIFE+ project at the Humberhead Peatlands is aimed at completing restoration activities across 2,887 ha that originally started in 2004 [68]. The Cumbria BogLIFE project[69] will restore 507 hectares on 3 lowland raised bogs in Cumbria (Bolton Fell Moss, Whedholme Flow & Roudsea Moss) Finally, the Exmoor and Dartmoor Mires on the Moors project aims to restore 2000 ha of blanket bog[70]. Further restoration projects are listed on the National Trust website[71] .Marches Mosses BogLIFE[72] received funding for the restoration of the Fenn's, Whixall & Bettisfield Mosses and Wem Moss NNRs.The Meres & Mosses NIA & Heritage Lottery Funding ran from 2012 to 2018[73]. The North of England Peatland Partnership received funding from the DEFRA Carbon Fund to restore 394 hectares of lowland raised bog and 1,679 hectares of blanket bog across 21 peatland sites.

- ***Wales: Mawndiroedd Cymru (Wales' Peatlands):*** The Welsh Peatlands Sustainable Management Scheme (SMS)[74] is aiming to restore bare and eroding peatland across the

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63 https://www.act-now.org.uk/cann
64 https://www.theccc.org.uk/wp-content/uploads/2013/07/ASC-2013-Chap4_singles_2.pdf.
65 https://www.yppartnership.org.uk/our-peatlands
66 http://www.northpennines.org.uk/our-work/peatland-programme/restoration/
67 https://www.gov.uk/government/news/peatlands-to-be-restored-in-the-north-west--2
68 http://www.humberheadpeatlands.org.uk/index.php?page=ourWork
69 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/601093/cumbria-boglife-project-leaflet.pdf
70 http://www.exmoormires.org.uk/index.cfm?articleid=8699
71 https://www.nationaltrust.org.uk/lists/key-peatland-projects
72 http://www.themeresandmosses.co.uk/page/74/marches-mosses-boglife-project.htm
73 http://www.themeresandmosses.co.uk/page/76/reports.htm
74 https://www.nationaltrust.org.uk/abergwesyn-common/features/welsh-peatland-sustainable-management-scheme-sms-project

Abergwesyn Commons, Ceredigion, Carmarthenshire, Brecon Beacons and across North Wales. More than 750 km of ditches have already been blocked across Welsh peatlands to restore and re-wet them, largely through management agreements with NRW and/or EU Life funding such as the ongoing LIFE Welsh Raised Bogs and the Anglesey and Llyn Fens LIFE project (Peter Jones, NRW,Pers. Comm.,[75]).In addition, there are substantive restoration efforts on the Welsh Government's Woodland Estate, including at least 10 sites comprising several thousands of hectares where work is ongoing or imminent [76]..

- ***OTs/OCs:*** The only known restoration activities are in the Falklands[77]. A range of small projects are ongoing to restore eroded and other degraded peatlands with appropriate native plants. Around 40 hectares of bare (eroding) peat have been actively revegetated in recent years (2014-2019) with good success in the short-term. Current work is primarily funded by, landowners, the John Ellerman Foundation (through Falklands Conservation), and the Antarctic Research Trust. The Darwin+ Project Building Capacity for Habitat Restoration in the Falkland Islands (completed in 2016) increased the suite of local restoration techniques to now include native seed collection and use to restore eroded areas.[78]

A compilation of all restoration locations for which site co-ordinates and areas rewetted could be obtained at the time of writing this update can be found in Figure 5

[75] https://naturalresources.wales/about-us/our-projects/nature-projects/anglesey-and-llyn-fens-life-project/?lang=en
[76] http://www.confor.org.uk/media/246255/peatland-restoration-april-2016.pdf.
[77] https://www.falklandsconservation.com/habitat-restoration
[78] https://admin.falklandsconservation.com/app/uploads/2018/10/FCAR-1718.pdf

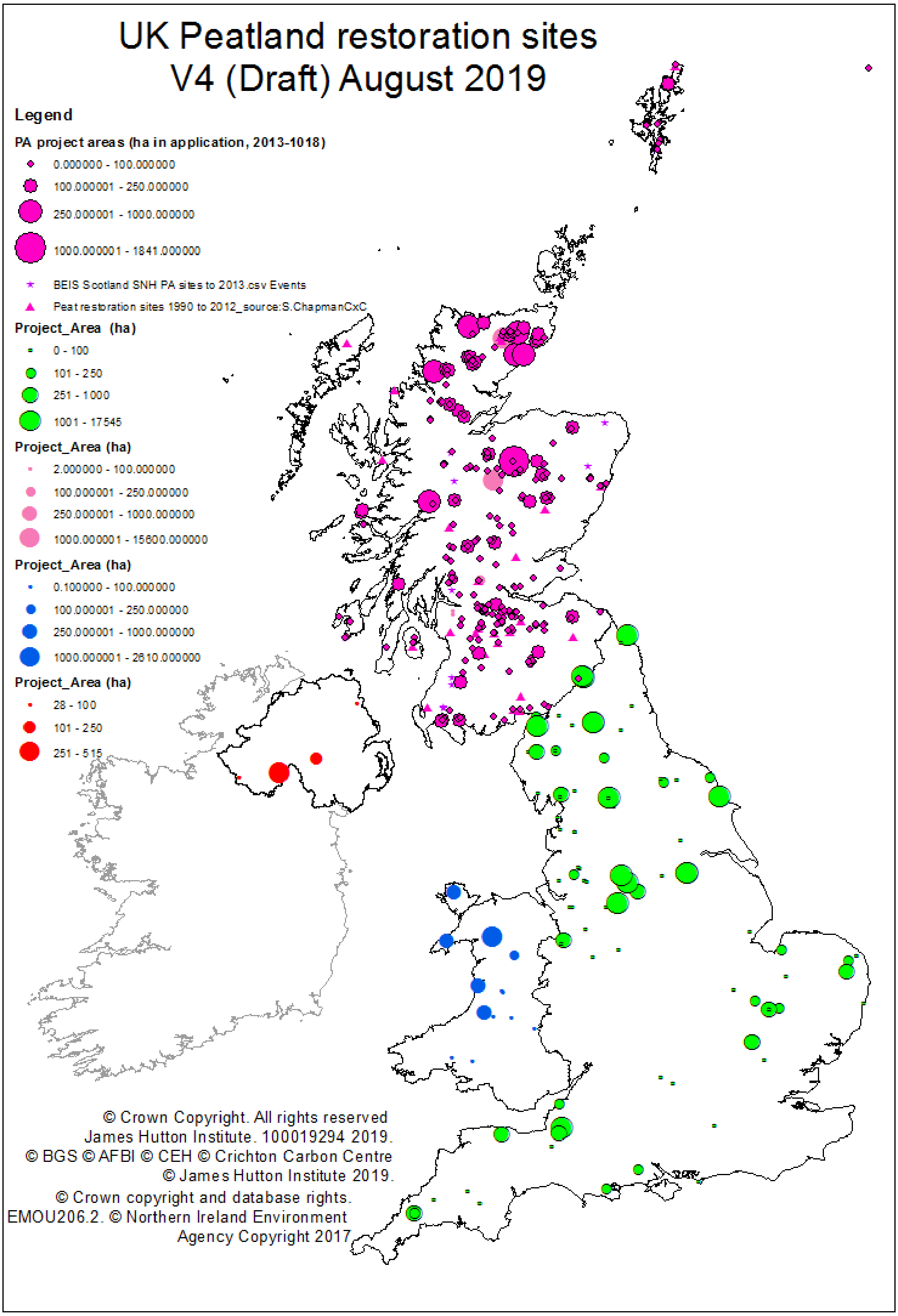

Fig. 5. Peatland rewetting sites in the UK according to area rewetted for Scotland (purples), Northern Ireland (red), England (green) and Wales (blue). **This dataset is likely incomplete and may contain inaccurate data on rewetting extent for some projects**. Data origjnate from the BEIS Inventory project and subsequent compilation for a follow-up BEIS project. Peatland Action (2013-2018, dark purple) data are from application stage and not yet verified on the ground in extent.

Techniques used to restore peatland

Lunt et al (2010) summarised the then standard methods of peatland restoration. Many of these are still in practice, but some new innovations have been made (Table 4). An interesting shift in focus from lowland raised bogs seems to have occurred towards large scale restoration on damaged upland, blanket, bog, as restoration techniques have been refined and proven to work under such more challenging conditions. The longer-term success rates/longevity of upland restoration relative to those observed on lowland sites still remain to be compared. By contrast, fen and lowland agricultural peat soils still appear to be largely neglected in terms of restoration focus, with some notable exceptions (e.g. Anglesey and Llyn Fens project; South Lincolnshire Fens; Mid Yare Valley; the Great Fen project; and the former arable land at Greylake nature reserve, Somerset). The handbook of methods and techniques to manage bogs (Conserving Bogs: the Management Handbook, Stoneman & Brooks) is currently being updated and should be available in a revised format soon[79]). In the Falklands, restoration requires a slightly different approach due to the different vegetation, land use, and climate. In the Falklands, restoration primarily involves removing or very carefully managing livestock and planting tillers of tussac (a peat forming grass which is eaten by livestock).Invasive species control and revegetation techniques using seeds, plug plants and a wider range of native species have also been used in small areas.

Table 4. Novel restoration techniques since 2010 (in green)- techniques existent in 2011 shown for completeness

Primary rewetting activity	*Individual activities within primary category*
Erosion control (gully blocking)	reprofiling, re-seeding, geojute application, native bog woodland recreation, channel damming
Ditch blocking	peat dams, plastic/heather/wood dams, trenching, bunding, cell bunding, reprofiling, channel damming; wave damming
Domestic and industrial extraction sites	Reprofiling, micro topographical variation, reseeding, applying a living carpet to establish vegetation quicker & more effectively[80]
Plantation forestry removal	Felling to waste (no longer in use due to sizes of current plantation trees), standard harvesting with stem removal, whole tree harvesting, whole tree mulching of failed tree crops, main drain blocking, furrow-blocking, silt traps, brash crushing, stump flipping/ground smoothing, brash mat removal, brash mulching.
Regeneration or scrub control	spraying, weed-wiping, hand pulling, cutting with brush/clearing saw, cutting with chainsaw, manual felling
Lowland agricultural sites	as covered above

Restoration cost

Restoration costs are still relatively poorly reported and further efforts to compile these would be beneficial. At present, published restoration costs still vary greatly (Table 5) but often the citations do not provide the detail required to understand why the discrepancies arise. It would be beneficial to understand the reasons behind different restoration costs in the context of access to nearest road, helicopter or other high-cost materials transport needs, site complexity and other geographical factors. There is often a need for management intervention post restoration, (e.g. conifer regen control, restoration of forestry roads and removal of fencing, in formerly afforested sites). Recurrent costs for post restoration management are not well reported in the literature but can be extremely costly. For example, removal of invasive regeneration of non-native conifer trees, where forestry plantations remain nearby, can be extremely costly, and non-native conifers are not legally classed as invasive non-natives, limiting funding options.

[79] http://www.iucn-uk-peatlandprogramme.org/node/2223
[80] http://www.themeresandmosses.co.uk/news/86/cumbria-boglife-project-film.htm

Table 5. Restoration cost summary from published literature or data compiled for typical (average) costs for restoration treatments in the Peak District and South Pennines SAC – capital works only

Type of restoration activity	Average (£ per ha)	Median (£ per ha)	Range (£ per ha)	Cost per unit (unit in brackets)	References
All restoration types combined	£830	880 or 1500 (including land purchase)	200-10,0000	-	Chapman et al (2012); Holden et al (2008); Andersen et al. (2017[81]);Artz and McBride (2017[82]); Moxey and Moran 2014); Smyth and Birnie (2013); Glenk and Ortega-Martin (2018)[83]
Drain blocking (ha)	879	517	-	-	Artz & McBride (2017); Moxey (2011)[84]; Grand-Clement et al (2015); Grand-Clement et al. (2013); Artz et al. (2018)[85]
Grip/gully blocking	-	-	-	25.32 (heather bale); 28.57 (peat); 95.30 (plastic); 120 (timber);162.98 (stone)	Maynard et al (pers Comm)
Hag Reprofiling	704	688	-	-	Artz & McBride (2017)
Restoring cutaway peat	300-5000	No data	-	-	Wilson et al (2012); Glenk and Ortega-Martin (2018)[86]
Living mulch on bare peat	2976	1487	-	-	Artz & McBride (2017)
Brash application	-	-	-	61.90 (bag, 49m^{2})	Maynard et al (pers Comm)
Geotextiles application	-	-	-	1.40 (m^{2})	Maynard et al (pers Comm)
Lime, seed and initial fertiliser	1,082.18;	-	-	-	Maynard et al (pers Comm)
Plug plants	2575	-	-	-	Maynard et al (pers Comm)
Sphagnum plugs	690 (or 419.75 at				Maynard et al (pers Comm)

[81] Andersen et al (2016), https://onlinelibrary.wiley.com/doi/abs/10.1111/rec.12415
[82] Artz and McBride (2017) Peatland restoration cost effectiveness Scotland https://www.climatexchange.org.uk/research/projects/peatland-restoration-methods-a-cost-benefit-analysis/
[83] Glenk and Ortega-Martin (2018) https://www.tandfonline.com/doi/full/10.1080/21606544.2018.1434562
[84] Moxey (2011) http://www.iucn-uk-peatlandprogramme.org/sites/www.iucn-uk-peatlandprogramme.org/files/Illustrative%20Economics%20of%20Peatland%20Restoration,%20June%202011%20Final.pdf
[85] https://www.climatexchange.org.uk/media/3141/peatland-restoration-methods-a-comparative-analysis.pdf
[86] Glenk and Ortega-Martin (2018) https://www.tandfonline.com/doi/full/10.1080/21606544.2018.1434562

	half density)				
Sphagnum clumps	612.50	-	-	-	Maynard et al (pers Comm)
Sphagnum translocation	462.50	-	-	-	Maynard et al (pers Comm)
Forestry mulching	2425	2425	-	-	Artz & McBride (2017)
Reprofiling	-	-	-	1.36 (m)	Maynard et al (pers Comm)
Peat dams and reprofiling (km)	1000	1000	-	-	Artz & McBride (2017)
Hag Reprofiling (km)	99.3	66.6	-	-	Artz & McBride (2017)
Cutting for diversity	742	-	-	-	Maynard et al (pers Comm)

Similarly, monitoring post-works requires funding. Moxey and Moran (2014) used a range of £25/ha to £400/ha for projects with minimal monitoring costs up to those with substantial opportunity costs, on an annual basis. The Peak District and South Pennines projects report a one time, maintenance, cost of £729.62 per hectare for areas previously limed, seeded and fertilised, using another lime and maintenance fertiliser application (Maynard et al., pers. Comm.). The IUCN Peatland Code briefing document for the business community[87] suggested costs in the range of £180 for further management over 30 years, and a further £126 per hectare for monitoring costs, which translates to costs in the range of £10 per hectare for monitoring and ongoing management costs. Opportunity costs may vary greatly depending on circumstances, as Moxey (2016)[88] and Smyth et al (2015)[89] illustrate.

Restoration trajectories – current state of knowledge

There are now a number of reports and peer-reviewed publications on the recovery of peatlands after restoration management has been completed. As a follow on for the Upland Evidence reviews (2013[90]) Natural England commissioned a series of reports to look at Blanket Bog recovery. These included collating information and data that were already being used by Peatland Recovery Partnerships across England. It is worth noting that the findings are particular to the very degraded blanket bog of the Pennines, England, and may therefore not be applicable to the recovery processes on less degraded blanket bog in e.g. parts of Scotland and Northern Ireland. The initial report was through a commission to Penny Anderson Associates (2014)[24] to review the evidence on the efficacy and timelines of interventions to move blanket bog towards favourable condition. This identified the following factors as the most frequent reasons for failure to meet Favourable condition on blanket bog sites: Inappropriate grazing; Managed burning; Drainage & dominance of vascular plant species (e.g.

[87] IUCN Peatland Programme. A new business opportunity to support UK Peatland restoration. Briefing for the business community. DRAFT August 2013. http://roar.uel.ac.uk/3590/3/BusinessBriefing%20DraftV5.pdf
[88] Moxey, A. 2016. Assessing the Opportunity Costs Associated with Peatland Restoration. IUCN UK peatland programme.
[89] Smyth, M.-A., E. Taylor, R. Artz, R. Birnie, C. Evans, A. Gray, A. Moxey, et al. 2015. Developing Peatland Carbon Metrics and Financial Modelling to Inform the Pilot Phase UK Peatland Code. Project NR0165, 1-23. Dumfries: Crichton Carbon Centre.
[90] http://publications.naturalengland.org.uk/category/5968803

Molinia and Calluna). Other factors less frequently reported were peat surface damage, wildfire/unmanaged burning, and invasive/non-native species. They did exclude a number of topics deemed to be to problematic in terms of evidence of success as a management intervention and evidence available to make recommendations. These comprise wild grazers, wild fires, peat pipes, bracken management, tree/scrub invasion, invasive non-native species.

This information was then related to the main management interventions identified to address the impact of failure factors. They made it clear that the interventions did not necessarily target one specific aspect (of favourable condition status) but instead contributed to providing the site conditions conducive to moving the habitat in the right direction. In this respect, most interventions benefitted from being in combinations tailored to the specific site issues and indeed some interventions needed to be paired to achieve success (for example, bare peat recovery requires stock removal). In broad terms all of the interventions work by reducing the dominance of plant species that are undesirable (or at undesirable cover/abundances) while at the same time enhancing those site conditions which support the preferred plant assemblages and ameliorating site conditions which limit the desired plant species assemblage (moving from dry degraded BB to much wetter bog conditions).

Reducing Molinia dominance per se can be achieved over a relatively short timeframe (approximately 5 years) where constant management effort is imposed. Achieving more diverse blanket bog vegetation is likely to require a 10 to 20-year time period, possibly longer for the full complement of six positive indicator species to be present. Altering grazing and removing burning has a number of complex effects on the vegetation. The general trend is for dominant species such as Calluna (ling or Common Heather) to decline over the long term. Eriophorum species (Cotton Grasses) and Empetrum nigrum (Crowberry) can also show similar patterns although the evidence is somewhat inconsistent for these species. Rubus chamaemorus (Cloudberry) and Narthecium (Bog Asphodel) can increase over the medium term, while the response of Sphagnum spp. is generally positive but different Sphagnum species do respond in different ways as they tolerate different hydrological conditions. Other mosses may increase and then decline over the longer term. In combination with other interventions (below) to increase the wetness of the sites will speed up this desirable transition to Sphagnum dominated wetland habitats again.

Grip blocking can raise water levels and increase water table stability, leading to increased water pooling immediately behind grips and associated vegetation colonisation. These could yield results over a very short timeframe (less than three years) in terms of a positive hydrological response Grip & gully blocking also effectively reduced sediment run-off. There is some indication that the effects can be seen across the wider catchment and include general increases in typical blanket bog species and reductions in species indicative of drier conditions. Associated vegetation responses to the altered hydrologic regime could take from 5 years in respect of re-vegetation of grips/gullies themselves to 10 years for changes across the wider vegetation community and in-filling of grips.

Reducing bare peat cover can occur within 5 years of the appropriate intervention measure, but this gives a vegetation cover that is atypical of blanket bog and fails on a number of other attributes including species diversity and cover/abundance of Sphagnum species. Ongoing improvement towards targets for these attributes can take another 10 to 15 years and possibly longer for targets such as the requirement for six positive indicator species to be present.

Peat pipes (pathway through the peat that water flows through) could be a significant barrier to achieving hydrological restoration on some sites, and research into management interventions to reduce the impact of peat pipe networks on blanket bog hydrology is required.

The degree of damage observed on either the peat surface or the bryophyte vegetation. Over-grazing itself can cause the loss of vegetation through the direct loss of plant material and increases in the dominance of species more tolerant of grazing or less readily grazed by stock. Effects can also be related to stock trampling impacts, including direct damage to vegetation/peat surface and compaction, along with input of nutrients from dung and urine favouring more competitive species. Compaction and damage can also occur from recreational pressure and vehicle use. Once exposed, the bare peat can be subject to continual erosion or reworking from frost heave and surface water run-off which can in turn reduce the potential for establishment of vegetation from seed.

As an addition to the Pilkington et al (2015)[53] report, Moors for the Future Peatland Partnership (MFFP) were asked to provide an inventory of published and unpublished examples that provide evidence of responses to land management and restoration interventions which indicate change (positive or negative change) with an assessment of timescales for delivery for each example. The aim is to produce a trajectory matrix which estimates the timescales required to deliver Favourable Condition. (Pilkington[91] et al. (2016) This summarises the effect of conservation works on key vegetation parameters by Moors for the Future Partnership (MFFP) North Pennines Area of Outstanding Natural Beauty (NPAONB) and the Yorkshire Peat Partnership (YPP).

The number of indicator species was seen as a very simple way of measuring trajectory of change: for example the presence of least 6 indicator species was proposed as a critical milestone which follows that of CSM for Blanket Bog, as was the Sphagnum moss cover over time, which was proposed as an alternative feature that may be measurable using remote sensing techniques

Water table was also considered a good indicator. The positive impacts of re-vegetation on the water table was seen across sites, although relatively small on an annual basis, it continued to accrue for periods in excess of 10 years. Comparison of the trajectories from early and late stage restoration suggests that more rapid changes may be occurring 10 years after restoration than in the first few years. Possible mechanisms include vegetation succession leading to changes in surface character and infiltration capacity, and/or progressive recovery of peat structure and hydrological function. While the positive impact demonstrated here is evidence for hydrological recovery associated with re-vegetation, complete restoration of water table behaviour in heavily degraded systems will be constrained by long term changes to peatland topography, due to the influences of erosional gullying.

The percentage areas of Bare Peat or Eroding peats has for a long time been seen as a very negative indicator of peat condition. These can then deteriorate further with Hagging and Gullying features.

Active blanket bogs are covered with vegetation which includes a relatively high percentage of Sphagnum mosses. The upper active layer of these systems (the 'acrotelm') controls exchanges of moisture with the atmosphere and has a relatively high hydraulic infiltration rate compared to the lower catotelm layer. These systems maintain the moisture level of peat above the water table at or near saturation even in dry periods so that even a small rain event will, relative to other non-peat systems, lead to rapid rises in water table and rapid generation of saturation-excess overland flow. The lowering of water tables to levels below the acrotelm in summer dry periods leads to sharp falls in through flow discharge which cuts off base flow and leads to a characteristically flashy system.

On blanket bogs devoid of vegetation, the absence of an active acrotelm slows infiltration rates, promotes radiative heating and increased rates of evaporation, drying the peat and lowering water tables. Deep erosional gullying is a major additional factor responsible for lowered water tables. Recent results from the Making Space for Water project (Pilkington et al., 2015[53]) have provided evidence that re-vegetation of bare peat was associated with raised water tables and increased generation of overland flow, the former potentially causing the latter. From the more recent analysis of a longer temporal dataset, there is now good evidence that the rise in water tables is linear, persisting over at least 10 years since the start of the restoration activities

RSPB have considered alternative protocols to the current SSSI monitoring system, as this does not adequately assess recovery. Groom (2015[52]) proposes a method that looks at indicating or tracking change at the site level. The Milestones approach sets triggers or milestones which can be used to determine whether a feature is improving or declining in condition and ensure recovery towards the desired states. Milestones are intermediates goals that can indicate changes in the condition or function of interest features in response to recovery activities. Milestones can help confirm short-term tangible successes such as the establishment of a nurse crop or reduction in the abundance of an invasive species. A series of corresponding milestones can help to guide the recovery process from the initial post –treatment phase towards the final target. This is particularly important when recovery to the desire state is going to take many decades or there is some uncertainty about the 'end-point'. Milestones should be developed based on the best available evidence, accepting that for many habitats and species the recovery trajectory is unclear. It is important to note that the rate and scale of

[91] Moors for the Future/ Pilkington, M., Walker, J. and Maskill, R. (2016) Trajectories for SSSI condition status of upland blanket bogs

recovery will be influenced by the management interventions undertaken; therefore, it is important to determine the management prescription required before attempting to set attainable milestones. In general, it is thought that the recovery trajectory of a heavily degraded habitat such as an area of blanket bog is likely to need higher intervention. It also needs to be acknowledged that environmental variable such as climatic changes, extreme weather events and wildlife fires all have the potential to alter a planned trajectory (Hobbs & Norton, 1996) and must be acknowledged when planning the accompanying management trajectory. The report then applies this approach across the RSPB & United Utilities Reserve at Dove Stones in the Peak District

The peer-reviewed literature is summarised in Annex Table 1 (some of which re-states findings from reports above), The majority of these were focused on single monitoring outcomes rather than a suite, potentially due to the more limiting format of a peer-reviewed publication. In addition, generally only a single timepoint has been considered and there has been no consistent approach to defining the target states. Another potential complication is that, as discussed in the earlier section of definitions, for a number of the studies where a nearby unmanaged control was used, this control area may have been affected by edge-effects of the interventions as those areas were sometimes quite small and surrounded by drained areas, or that the control areas are themselves adversely affected by historic impacts. They may nevertheless be a valid target state for a restoration area – which may have suffered the same historic impacts as well as additional ones.

The target state can be expected to be dynamic – many designated bogs in good condition are recovering slowly from past impacts (e.g. fires); there is also potential for change in intact bogs, in response to climatic events or trends, or reductions in deer or sheep densities (which are tending to occur quite widely in some areas). If the reference site changes over time, then it is reasonable to say that the target state has also changed (usually subtly) over time. The restoration site will need to track the target site and ultimately converge with it. However, over 70% of the publications to date report a beneficial effect of the restoration management, with only a very small number of reports of negative effects such as transient effects on water quality (Annex Table 1; Figure 6).

External influences on the path or direction of restoration trajectories are mentioned in many of the compiled literature in Annex Table 1. Hancock et al (2018)[54] cite topographic factors (including legacies of the former management) such as site slope and remaining plough ridges, but also highlight that the target state, in terms of vegetation, may have changed in the time since restoration efforts began. Brown et al (2016) speculate whether local air quality may influence recovery of macroinvertebrate communities in bog pools in the North and South Pennines. Qassim et al (2014) suggested that the lack of positive outcomes in their studies was in part due to incomplete restoration management and suggest that the outcome would have improved if water table management had been applied.

This is also stated in Andersen and Peace (2017) where the trajectory of recovery after afforestation was critically dependent on drain blocking measures having been applied. Williamson et al. (2017[56]) found limited evidence of water table or vegetation recovery at a range of ditch-blocked sites in North Wales, which they attributed partly to the fact that the drained peat area had partially subsided towards the water table in the vicinity of the ditches, and partly to slow rates of vegetation change. Recent climatic change appears to not influence carbon sequestration rates at present in undamaged sites (Lunt et al, 2019)[92], however there is evidence in the wider literature that extreme climatic years can affect outcomes (e.g in Gatis, 2015). Ultimately, using a nearby reference site as target state allows the target state to remain realistic, in terms of what happens in the region, rather than frozen in time according to some past definition of 'restored'

[92] Lunt et al (2019) https://www.sciencedirect.com/science/article/pii/S0048969719307375

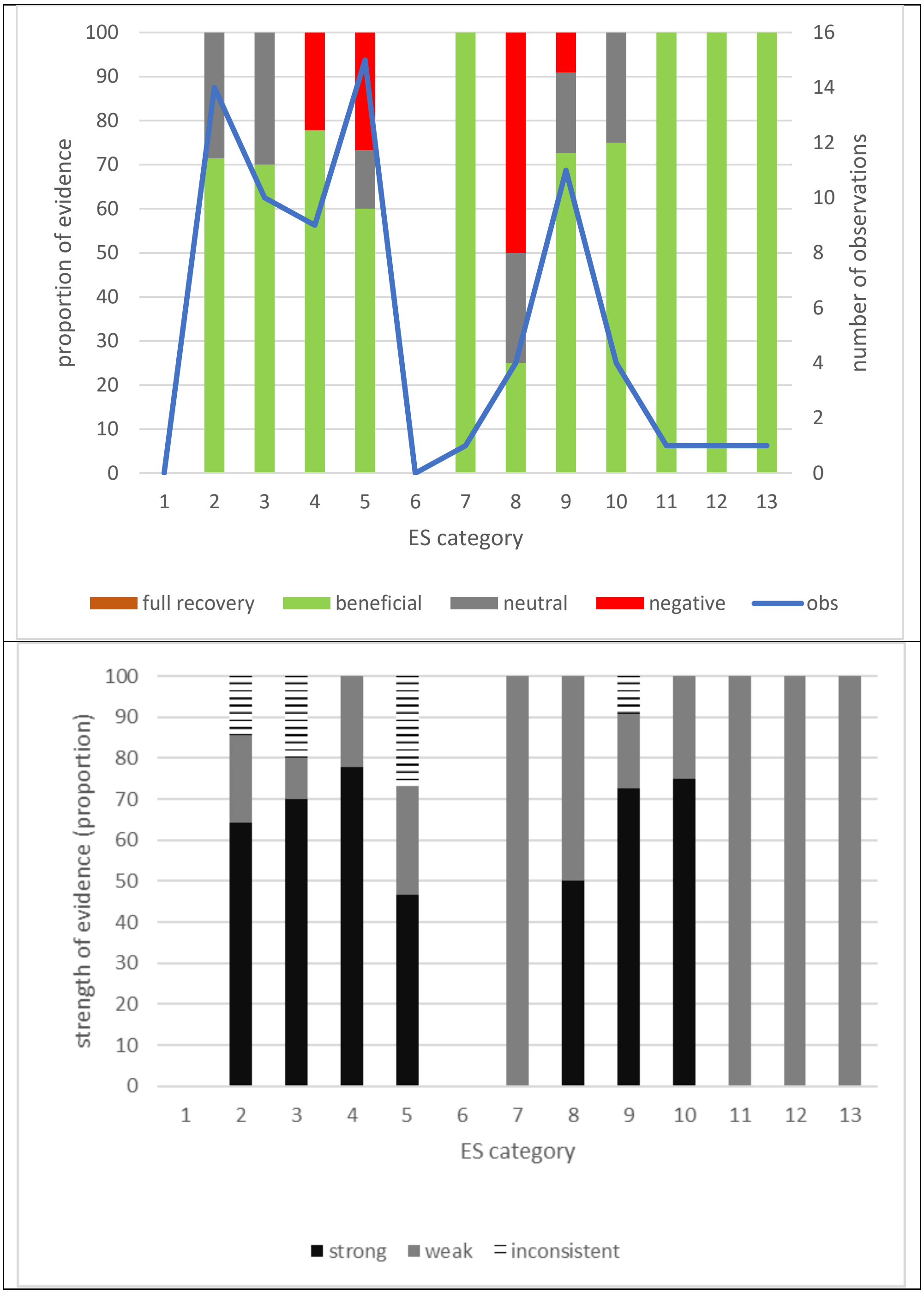

Fig. 6. Estimated state of the evidence of the effectiveness of peatland restoration in achieving a functional peatland ecosystem (based on ecosystem services and functions in Table 2). Upper: Proportion of evidence showing full recovery, beneficial, neutral or negative effects by ES category, and showing the number of underpinning observations on the secondary axis. Lower: Strength of the evidence, showing the proportion of strong, weak or inconsistent evidence by ES category.

In addition to the peer-reviewed publications and PhD theses summarised in Figure 6 and Annex Table 1, there are now a number of publications that attempt to summarise the effectiveness of restoration using multiple indicators. The aforementioned Natural England Review of Upland[93] evidence review on restoration of degraded blanket bog used an evidence statement-based

[93] Shepherd, M. J., Labadz, J., Caporn, S. J., Crowle, A., Goodison, R., Rebane, M. &Waters, R. (2013) Natural England review of upland evidence - Restoration of Degraded Blanket Bog. Natural England Evidence Review, Number 003.

approach, by which data from literature were assigned to qualitative statements of the strength and magnitude of the evidence to date. The report assessed the evidence on drivers of degradation in blanket bog as well as the conditions and required interventions for restoration but stopped short of formally assessing restoration trajectories or summarising these multiple indicators. The NEROS network[94] used a common methodology to assess restoration success across a number of restored peatlands in Ireland. Four core components were assessed: a) hydrological integrity, b) physico-chemical parameters (e.g. pH, C:N ratio); c) micro-habitat heterogeneity and condition and d) vegetation composition, including key positive and negative indicator species. The authors used radar plots to show effectiveness across multiple indicators of success. Others, e.g. Alderson et al (2019[51]) graphically summarise the combined findings for several indicators of restoration success as well as in summary table format. The Exmoor Mires Restoration Project reported on a number of indicators of improvement, mostly in narrative form[95].

Penny Anderson Associates (2014)[24], as also mentioned previously, reviewed evidence of effects of various management interventions including active rewetting but also grazing reduction/cessation of prescribed burning on blanket bog condition for Natural England. The report discussed the various factors influencing the rate of recovery of blanket bog towards favourable condition, as defined by the Common Standards Monitoring targets. The report then examines the relative impact of different interventions, including restoration techniques, on recovery, including potential timelines to achieve the target and aspects of applicability and limitations.

Finally, Moors for the Future Partnership's extensive conservation activities on degraded areas of blanket bog (Buckler et al. 2013)[96] provided the basis for a major study investigating the temporal development of the emerging vegetative community and its consequences on erosion rates and hydrology (Pilkington et al. 2015[53], Shuttleworth et al 2019[97], Alderson et al. 2019[51]). In this study, the cover of different plant species/functional types was monitored at more than 20 sites across the three major plateaux of the Dark Peak (Black Hill, Bleaklow and Kinder Scout) with some additional sites in the South Pennines (Rishworth and Turley Holes). Some of the sites were re-vegetated as far back as 2003, and have been monitored approximately annually since, but most were re-vegetated at various times since then and were monitored for shorter spans of time. The overall conclusion from this study suggested that following revegetation there is a strong and relatively rapid decline in the cover of bare peat with concomitant increases in the cover of total vegetation - clearly an indication of the success in terms of preventing exposure / drying of peat, of the lime, seed and fertiliser treatments. There were also clear trajectories showing increases in both the cover and the count of blanket bog indicator species (see example, Fig. 7), with some of these trends appearing to slow over time, beyond which no significant further improvements occurred. Nevertheless, these developments were found to have statistically significant and positive effects, reducing particulate erosion rates and storm run-off. The amount of particulate peat held in suspension in gully flow was reduced by more than 90% within a few years. After one year, the flow of water coming off the bog during storms was reduced, while taking longer to reach its peak. Water tables rose steadily over a 12-year period following restoration and ongoing work is investigating the effects on water quality, including colour. While these results present strong beneficial effects across a wide spectrum of ecosystem services, it should also be noted that the rate and shape of the improvement was found to have relatively high variability, potentially reflecting variations in spatial topography, temporal meteorological conditions as well as differences in the restoration treatments used. Examining this kind of information is an important next step in adaptive management process

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[94] Renou-Wilson et al (2018) Network Monitoring Rewetted and Restored Peatlands/Organic Soils for Climate and Biodiversity Benefits (NEROS). http://www.epa.ie/researchandeducation/research/researchpublications/researchreports/research236.html

[95] Exmoor Mires Restoration Project, Final Report (2010) http://www.beachlive.co.uk/media/pdf/f/p/mires_review_final_report_1_.pdf

[96] Buckler, M., Proctor, S., Walker, J.S., Wittram, B., Straton, P. and Maskill, R.M., (2013) Moors for the Future Partnerships restoration methods for restoring bare peat in the South Pennines SAC: evidence-based recommendations. Moors for the Future Partnership, Edale.

[97] Shuttleworth, E. L. Martin G. Evans, Michael Pilkington, Thomas Spencer, Jonathan Walker, David Milledge, Timothy E.H. Allott (2019) Restoration of blanket peat moorland delays stormflow from hillslopes and reduces peak discharge. Journal of Hydrology X, Volume 2. https://www.sciencedirect.com/science/article/pii/S2589915518300063

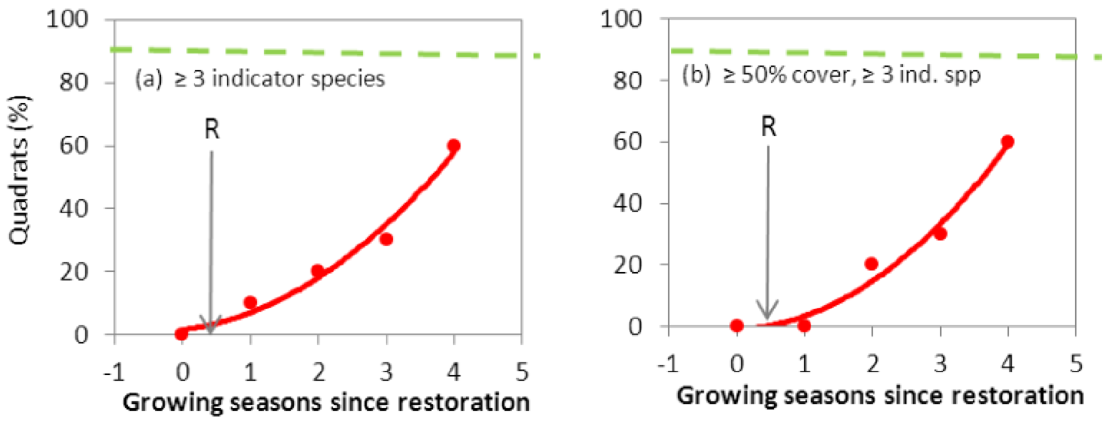

Fig 7. Example of restoration trajectory findings shown against individual criteria for favourable condition of blanket bog in the CSM methodology (green dotted lines).. From Making Space for Water project Final report summary (Pilkington et al., 2015[53]).

Data gaps in assessing restoration

Whilst there are now an encouraging number of reports from peatland restoration monitoring, the vast majority of these address hydrological functioning or vegetation composition as indicators of success. There is little information on even the vegetative composition of well-functioning peatlands in OTs and these are major data gaps amongst global efforts to improve species monitoring[98]

In general, there is a lack of long-term monitoring studies, and a lack of use of control sites for both initial (damaged) and target (intact but not perfect) state.

The UK, there are a number of significant data gaps in particular areas. In forestry studies, for example, the very significant impacts of forest roads and fences tend to get ignored. Peatland emissions monitoring is still generally lacking, as a recent report that compiled currently available data on peatland emissions as part of scoping for country-specific Emission Factors for UK national emissions reporting pointed out (Evans et al., 2017[5]).

Despite the clear high potential to gather monitoring data at high temporal frequency, there have been only a couple of studies where Earth Observations have been used to monitor peatland restoration effectiveness. With Sentinel satellites having been recently launched, the next few years will presumably see a major expansion in this area of monitoring.

There is also at present no clear guidance on how to guide the restoration process from the outset. Bonn et al (2016)[99] suggest that assembly rules theory could be used to guide restoration management, by identifying target vegetation species prior to commencing work through a comparison of species present in the site to be restored against the species pool in a compatible reference area. The restoration management should then aim to improve environmental conditions and minimise dispersal constraints for these species. Post-restoration management should also include assessment of dynamics with competing species.

In many restoration projects, multiple indicators of success are being monitored, yet rarely is there a framework by which all can be assessed on a common scale. If such common frameworks existed, projects could be assessed through time and compared against each other, using scaled sums of

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98 https://www.cambridge.org/core/services/aop-cambridge-core/content/view/091CF2167D91764E826145946A792F17/S0030605318000509a.pdf/global_effort_to_improve_species_monitoring_for_conservation.pdf

99 Bonn et al (2016) Peatland Restoration and Ecosystem Services -Science, Policy and Practice. https://www.cambridge.org/core/books/peatland-restoration-and-ecosystem-services/0626216ED0DECB81F5764A412859F2E7#fndtn-information

change in the indicators. Some elements would require to be assessed for scalability of the findings. Firstly, are data from restored area of different sizes comparable, i.e. are there limitations to rewetting success due to area/fragmentation and /or greater variation among a sample of smaller areas, compared to a sample of larger areas? This could be assessed statistically once a few projects have used the same framework for reporting, i.e. are the trajectories slower in e.g. smaller, more fragmented, higher-altitude, higher latitude, more sloping, less intensively restored, nearer climate envelope edge etc., restored peatlands. Secondly, sampling density of the data for the indicator (spatially and temporally) will affect the confidence level attributed to the relevant data sources (i.e. single dipwell monitored monthly before and after restoration is better than nothing but not the same quality as a grid of water level logger data). This could be compiled as a confidence level of the assessment. It is possible to use these as weights in a comparative framework.

A final data gaps is in the potential timelines it may take to achieve the target state, and this is related to the relative lack of long-term monitoring data. Do we spend more money on restoration at a given site, in order to get faster recovery, or do we spend the same money elsewhere, to put a larger area on a slow trajectory to recovery? Answering this question would require better quantification of recovery rate against management spend, and modelling against overall government C commitments (i.e. there will some optimum way of spending the budget in terms of climate benefits, by a particular endpoint).

There is thus considerable potential to develop a common reporting framework for peatland restoration trajectories. However, a suitable assessment should include all potential users of these data, perhaps using the example of the scoping exercise for the Natural Resources Monitoring Framework (Wales)[100]. There are currently some ongoing projects to develop peatland monitoring strategies, both at potential UK and international level (e.g. the Global Peatlands Initiative).

Future commitments to peatland restoration

This section intends to provide a brief update to the 2011 review, which reviewed public funding for peatland management and restoration[101]. There have been some significant shifts away from the predominantly agri-environment management agreements-based system for the delivery of restoration, although this still remains the predominant instrument for longer term management. Restoration activities are now receiving significant levels of more targeted funding (see below), although often there is still a high requirement for co-funding from other sources (private, EU). A shift in policy towards considering peatland management and restoration as a valuable contributor towards reducing UK greenhouse gas emission in addition to the biodiversity benefits has been a contributing factor in this more targeted funding.

Legislation and policies

The UK Climate Change Act (2008)[102], alongside legal instrument for each of the Devolved Administrations (e.g. Climate Change (Scotland) Act 2009; Climate Change (Emissions Reduction Targets) (Scotland) Bill (now amended with a 2045 deadline for delivery of zero carbon); Environment (Wales) Act 2016, set emissions reductions targets for the UK and DA’s. There is as yet no formal recognition that peatland restoration and optimal management can play a significant role in achieving

[100] Emmett, Bridget; Bell, Chris; Chadwick, David; Cheffings, Chris; Henrys, Peter; Prosser, Havard; Siriwardena, Gavin; Smart, Simon; Williams, Bronwen. 2016 Options for a new integrated natural resources monitoring framework for Wales. Phase 1 project report. Bangor, UK, NERC/Centre for Ecology & Hydrology, 57pp. (CEH Project no. C05945) http://nora.nerc.ac.uk/id/eprint/515663/1/N515663CR.pdf

[101] Keenleyside, C. and Moxley, A. (2011) Public funding of peatland management and restoration in the UK- a review. Available at: http://www.iucn-uk-peatlandprogramme.org/sites/www.iucn-uk-peatlandprogramme.org/files/Review%20Public%20Funding%20of%20Peatland%20Management%20and%20Restoration,%20June%202011%20Final.pdf

[102] http://www.legislation.gov.uk/ukpga/2008/27/contents

these targets, in part because emissions from degraded peatlands have not yet been fully considered in national emissions accounting. However, some of the preliminary analyses on the potential carbon savings from restoration have translated into explicit inclusion of peatlands in national level policy related to reducing emissions (e.g. the 5th Carbon budget; Scotland's Climate Change Plan) even though restoration targets in the e.g. Climate Change Plan are set to achieve the more accepted biodiversity benefits of restoration. 'Prosperity for All: Low Carbon Wales 2019' similarly highlights peatland management in relation to the potential emissions reductions, in anticipation of a likely future change to the UK Emissions Inventory to more appropriately account for peatland emissions. Other environmental legislation has been largely updated to reflect international changes in legislation, for example, the Conservation of Habitats and Species Regulations (2017) Act and the Environment Act (Wales) 2016. Peatlands also feature in policy documents aimed to fulfil the statutory requirements of conservation legislation. For example, the Nature Recovery Plan for Wales (2015), the 2020 Challenge for Scotland's Biodiversity, and Biodiversity Strategy for Northern Ireland to 2020 all explicitly make reference to peatland conservation and restoration aims, although not all have explicit targets. Biodiversity 2020: A strategy for England's wildlife and ecosystem services, on the other hand, does not specifically reference peatland.

Specific policy instruments

Government-level policy instruments specifically aimed at delivering peatland restoration vary across the UK. In England, a £10 million grant scheme to restore England's iconic peatland was announced in 2017. In Scotland, Peatland Action is the instrument charged with delivery of the peatland restoration targets in the Climate Change Plan and has been running since 2012. In Wales, much peatland restoration work has been funded through Natural Resources Wales management agreements with landowners and through EU LIFE funding. The Welsh Government has also made significant investment in peatland restoration and management through its agri environment scheme Tir Gofal, its sustainable land management scheme Glastir and more recently through the Nature Fund.The £1m Mawndiroedd Cymru (Wales' Peatlands) project (2017) also aims to aid delivery of restoration through training. Northern Ireland: With the lack of a specific programme, the only specific policy instrument to deliver the aims of the peatland ambitions of the Biodiversity Strategy for Northern Ireland to 2020 stem from a single stated project: Delivery of peatland and wetland habitat restoration around the Lough Neagh Basin ("Futurescape") through support for "Rebuilding the Countryside Programme for 2015/16.

Policy barriers:

Despite considerable efforts to improve target setting for peatland restoration for biodiversity, water and carbon benefits, additional funding options having become available, and improved knowledge on how to carry out restoration, there is still only a relatively small amount of restoration being delivered and it is therefore likely that the IUCN UK Peatland Programme target of having 1 million hectares of peatlands in good condition or under restorative management by 2020 will be missed. In a world where global warming of less than 2 degrees Celsius is looking increasingly unlikely, this would be a disappointing outcome.

One of the major barriers remaining to develop consistent policy to deliver peatland restoration is that there is not yet an accounting mechanism for the mitigation achieved by restoration until the UK formally adopts wetland reporting as per the IPCC Wetland Supplement (2014) recommendations. Ongoing work in this area (Evans et al., 2017[5]) suggests that the still relatively low data availability of the potential carbon savings and the lack of a suitable reporting framework for the areas of peatland under different types of land cover constrain the development of a robust method for the implementation of emissions reporting. This is likely is a contributing factor that may limit the setting of more concrete restoration targets and further development of some of the national policy instruments. The Committee on Climate Change (2019)[103] used data from Evans et al (2017[5]) to calculate the potential carbon mitigation from peatland restoration efforts as part of its wider assessment of potential strategies to deliver net zero by 2050 and recommended under its Further Ambitions option that efforts should be increased to a target of 55% of land area restored (i.e. 1,63 million hectares across the UK in good condition) by 2050. This would mean delivery of up to 800,000 hectares of restoration management over the next 31 years, if our estimates of the currently completed

[103] https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/

restoration effort (Table 3) are correct. At the average cost estimates in Table 4, this would clearly require significant investment. Additional progress has been made through the adoption of the Sustainable Development Goals, of which 15 (Life on Land) specifically refers to ecosystem restoration. However, there are no specific goals for peatlands as such in the original SDG, and the UK has largely taken its lead from the EU 2020 Biodiversity Strategy, which sets a target for 'restoring at least 15 % of degraded ecosystems'. Clearly, some time has passed since the development of the various biodiversity strategies, but the contrast between the relatively modest biodiversity targets and the recommendations of the Committee on Climate Change is stark.

In terms of wider peatland management, at the time of writing, the largest underpinning funding is still through support under Rural Development Programme funds the EU Common Agricultural Policy. RSPB pointed out in a (201X) document[104] that there are a number of limitations to the Common Agricultural Policy for supporting appropriate management, for example the lack of assessment of the ecosystem's carrying capacity in payments for grazing livestock. The future CAP (2021-27) looks to include a specific new conditionality for funding to increase 'Preservation of carbon rich soils such as peatlands and wetlands' (new proposed GAEC 2[105]). At the point of writing, the UK is still a member state with the current UK Government having expressed a desired exit date of October 31st , 2019. In a post-Brexit UK, whatever shape the future replacement of the Common Agricultural Policy and the Environment LIFE programme will take, these instruments will play a significant part in the likely outcome for UK peatland restoration[106]. Whilst some alternatives through private financing exist, such as through Payment-for-Ecosystem-Services (PES) and recognised market standards e.g. the Peatland Code, these currently make up only a proportion of the delivered restoration to date. This also includes co-funding through e.g. water suppliers, which has been a more considerable co-funding option to date. Here, changes in future regulation may affect what vehicles for funding peatland restoration may be available to achieve drinking water and environmental standards for public water supply catchments.

Threats to peatland condition and restoration success

There are numerous threats to peatland condition and restoration success and this topic is in itself worth exploring in a separate report. Current global policy commitment is likely to result in about 3.3°C warming above pre-industrial levels by 2100, which may put severe pressure on UK peatland functioning in itself, as well as an increased risk of invasive species. A recent UK Parliamentary Briefing[107] concluded that 'UK climate projections indicate that climatic factors conducive to elevated wildfire conditions will increase' and that 'The UK Climate Change Risk Assessment and National Adaptation Programme identified wildfire as a climate change risk'. Severe wildfires have the capacity to not only impact vegetation composition and greenhouse has exchange, a fire burning into the peat leads to direct losses of soil carbon that may have accumulated for decades of more. Historic atmospheric nitrogen and sulphur pollution continues to be a limiting factor in the success of peatland recovery[108]. Continued grazing pressure above the ecosystem's carrying capacity [109] or otherwise inappropriate grazing features in many assessments of limited recovery after restoration management as a potential contributing factor and its impacts have been summarised by Penny Anderson Associates (2014)[24]. This report also examines the importance of managed burning and drainage. A final threat is in the direct loss of peat through development. It is currently not known what area and/or volume of peat(land) is lost to development for e.g. wind farms, roads or other infrastructure.

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104 https://www.rspb.org.uk/globalassets/downloads/documents/positions/agriculture/realising-the-benefits-of-peatlands.pdf
105 https://ec.europa.eu/info/news/environmental-care-and-climate-change-objectives-future-cap-2019-jan-25_en
106 https://www.iucn-uk-peatlandprogramme.org/sites/default/files/2019-07/170109%20IUCN%20Brexit%20document_WEB.PDF
107 https://researchbriefings.parliament.uk/ResearchBriefing/Summary/POST-PN-0603
108 https://www.iucn-uk-peatlandprogramme.org/sites/www.iucn-uk-peatlandprogramme.org/files/13%20Atmospheric%20pollution.pdf
109 https://www.iucn-uk-peatlandprogramme.org/sites/default/files/2019-05/7%20Grazing%20and%20trampling%20final%20-%205th%20November%202014.pdf

Recommendations

- A major obstacle in measuring success is the lack of a common definition of a target state, and the lack of a common framework for monitoring and reporting. In terms of vegetation monitoring, the Common Standards Monitoring framework is the only common standard that can be applied at present, however it is generally only used for designated site monitoring. It does, however, use a standardised method to score degradation factors as part of the wider site condition assessment methodology. This lack of a common framework requires to be addressed.
- Currently there is no monitoring framework in place in relation to international obligations regarding restoration (Aichi 15) targets or the UK's obligations to report GHG emissions under the UNFCCC and Kyoto Protocol. Biodiversity and wider condition monitoring are still limited to only having a framework for monitoring for designated areas, but reporting intervals are limited and are consistently being missed. There is therefore still no robust estimate of how much of the UK peatland resource is in good condition, poor condition, and/or deteriorating due to climate change. A wider UK peatland monitoring framework, that dovetails with international procedures and requirements should address these critical issues.
- Reporting on extent of 'restored' peatland. Methodologies to prove the extent of successful rewetting need to be developed to ensure a common (and possibly mandatory, in the case of publicly funded projects) future reporting protocol can be developed for national level reporting. Collation of these data may require a decision on an appropriate centralised body at UK or Devolved Administration level for data handling .
- Cost of peatland restoration needs to be reported better, using standardised methods. A better estimate of the cost of restoration in the light of the recommended targets by the Committee on Climate Change would enable better projections of overall cost and thereby allow better alignment of future policy instruments.
- Consider mapping benefits to multiple ecosystem services even if these cannot yet be fully quantified or monetarised. A common scalar could be developed for the systematic assessment of the various potential ecosystem service impacts and this would enable a critical comparison of inter-site restoration success.
- Raise the profile of the (substantive) peatlands in the UK's Crown Dependencies and Overseas Territories and support their work to better describe and understand their ecology, processes, threats and practical restoration.
- Restoration grant aid should fund a level of on-site monitoring appropriate to the uncertainty of the outcome. Monitoring should take place in the restoration area and also in a comparable reference site in the same region, that represents a suitable target state for the restoration site. Reference sites do not need to be fully 'natural' or 'pristine' but could be (for example) intact designated nearby peatland sites at similar altitude and slope, assessed as being in good condition under statutory condition assessments. Reference sites should not contain any unrestored impacts (e.g. unblocked drains). This ground monitoring should be complemented by collating remote sensed indicators of vegetation and moisture conditions from the same sites for the monitoring years. Monitoring funding should be maintained long-term so that periodic (e.g. every few years), updated assessments can be made over many years, gradually building knowledge on long term responses of peatland sites to restoration management, as compared to suitable reference sites
- Future policy development in Climate Change, Biodiversity, Planning and Agricultural arenas, especially post the (currently still ongoing) Brexit process, should explicitly regard the specific need of peatland restoration and conservation goals, given their importance for greenhouse gas emissions mitigation and in delivering UN Sustainable Development Goal 15.

Annex Table 1. Restoration outcomes – synthesis of published evidence from UK-based restoration monitoring projects (studies using laboratory incubations of samples from restoration sites were excluded).

Citation	Restoration outcome monitored	Reference target state	Timescale	Outcome
Hancock et al., (2018)[54];	Vegetation recovery in formerly afforested restored blanket bog, where restoration work had started in the late 1990s	Nearby control (intact, designated sites managed by extensive deer grazing only, hill drains having been blocked)	Up to 17 years post management	Initial convergence towards target state but more recent (7-14 year) results suggest weak trend towards more heath-like vegetation in former plough ridges and original surfaces, whilst former furrows continued on trajectory towards bog target. Floristic similarity to target decreased overall, reflecting the development of heath-like vegetation in drier parts of the study area. Ellenberg R (pH-linked) and N (nutrient-linked) values decreased, but F (moisture-linked) values increased. Overall, moisture-linked indicator values converged well with the intact bog reference sites, but clear differences remained after 14 years in the pH- and nutrient-linked values. Residual deer presence and the forestry road (potential for mineral dust enrichment) are wider scale factors potentially slowing full recovery of this study site.
Peacock et al., (2018)[110]	Dissolved organic matter (DOM) quality in sites where ditch blocking has been applied	Pre-intervention control	Up to 4 years post management	No clear evidence of improvement (or deterioration) in water quality
Armstrong et al (2010)[111]	Dissolved organic carbon (DOC) loss and water discolouration in blocked vs unblocked drains	Unblocked controls	Up to 7 years post management	General pattern of lower DOC and water colour from blocked drains, though some inconsistencies were observed
Andersen and Peace, (2017)[112]	Water table depth, peat bulk density, water content, ground surface height and vegetation development on formerly afforested blanket bog	Nearby undrained and unplanted blanket bog	Up to 10 years post management	Water level recovery to near, but not to, control levels, but only in sites where felling was combined with damming drains. Vegetation recovery towards the control after 5 years. Decreased bulk density, increased water content and increased ground surface height. Regeneration of trees from seed was observed.

[110] Peacock et al (2018) https://onlinelibrary.wiley.com/doi/10.1002/hyp.13297
[111] Armstrong et al (2010) https://www.sciencedirect.com/science/article/pii/S0022169409007513
[112] Andersen and Peace (2017) http://mires-and-peat.net/media/map19/map_19_06.pdf

Holden et al (2018)[113]	Pool water level fluctuations in pools formed through drain blocking	Natural blanket bog pools	11-14 years post management	Pool water levels fluctuate more in relation to weather events and have higher rates of replacement of their volume. Water table depths near artificial pools also fluctuate more.
Brown et al (2016)[114]	Macroinvertebrate communities in pools formed through drain blocking	Undrained blanket bog pools	5-10 years post management	Different metrics produce different outcomes: Analysis of community composition showed small but significant differences, whereas analysis of diversity metrics did not. Assembly process comparisons showed generally similar levels of stochasticity, which provides further evidence of restoration success.
Qassim et al (2014)[115]	Water table and quality effects, as well as vegetation recovery, of lime and fertiliser treatment in combination with a nurse grass application to bare peat on formerly eroded and/or fire-damaged sites	Nearby vegetated control channel	3-9 years post management	No significant improvement in water table, Soil porewater DOC increased.
Turner et al (2013)[116]	DOC concentrations, DOC export, and water yield at a drain blocked catchment	No target state comparison; control was unblocked references	1 year pre-management and >1 year post management	Decline in DOC only significant at first order scale; significant reduction of water yield in the drain and thereby reduced DOC export, with increasing effect between zero and first order drains. Some evidence of flow bypassing drain-blocking structures.
Wilson et al (2016)[117]	Greenhouse gas emissions due to rewetting (review); used for default emission factors in the IPCC Wetlands Supplement	Relative controls of near-natural states	Various up to 30 years post management	Reductions in carbon dioxide (CO_2) emissions, nitrous oxide emissions and DOC losses, coupled to increases in methane (CH_4) emissions relative to the non-rewetted state. There was no significant difference within the wider temperate region relative to the target state for CO_2 and CH_4 emissions, suggesting very successful restoration outcomes.

[113] Holden et al (2018) https://onlinelibrary.wiley.com/doi/full/10.1002/hyp.11438
[114] Brown et al (2016) http://eprints.whiterose.ac.uk/101984/
[115] Qassim et al (2014) https://www.sciencedirect.com/science/article/pii/S0022169414008993
[116] Turner et al (2013) https://www.sciencedirect.com/science/article/pii/S0022169412010384
[117] Wilson et al (2016) http://mires-and-peat.net/media/map17/map_17_04.pdf

	(global analysis including UK data)			
Peacock et al (2019)[118]	Net ecosystem carbon balance on a former cropland on peed fen peat, converted to grassland	Local conservation site, and remaining cropland on peat, as references	19-21 years post management (with ongoing annual water management)	Compared with the grassland converted site, the conservation fen resulted in better carbon mitigation, although both sites had lower carbon losses than a cropland system on peat.
Alderson et al., (2019)[51]	Vegetation cover, indicator species, water table, runoff and water quality in areas restored using gully blocking and lime and fertiliser treatment in combination with a nurse grass application to bare peat	No target state sites, used degraded state as starting reference and targets from national monitoring schemes for	0-12 years post management for vegetation and water table depth; shorter monitoring periods for the other indicators	Major progress and modellable trajectory towards achieving targets as set by the Common Standards Monitoring protocol with regards to indicator species count and % cover and reduction of % cover of bare ground, Linear trends of water table depth recovery towards the surface. Immediate decrease in peak storm discharge and increases in lag times. No trend in% runoff. Early reduction in POC losses, but no evidence of a trend in DOC concentrations.
Gaffney et al; (2018)[119]	Water chemistry indicators and water table depth on formerly afforested sites	Local unmanaged and undrained blanket bog	0-17 years post management	Progress towards the target state, but not complete recovery, for water table depth, pH, DOC, aluminium, zinc and ammonium. Phosphate and potassium levels recovered within 11 years.
Edopka et al., (2017)[120]	Dissolved nitrogen in first-order catchments	Nearby intact site	3-4 years post management	Reduction of inorganic N leaching by up to 90%.
Bellamy et al., (2012)[121]	Vegetation changes on drain-blocked blanket bog	No target state, compared	4-11 years post management	Conflicting evidence, with most consistent trend for a positive trend in species indicative of recovery in oldest sites

[118] Peacock et al (2019) https://www.sciencedirect.com/science/article/pii/S0167880918304018
[119] Gaffney et al (2018) https://www.sciencedirect.com/science/article/pii/S0301479718304948?via%3Dihub
[120] Edopka et al (2017) https://www.sciencedirect.com/science/article/pii/S0925857417302732
[121] Bellamy et al (2012) https://onlinelibrary.wiley.com/doi/full/10.1111/j.1654-109X.2011.01151.x

		with unblocked drains		
Dixon et al (2014)[122]	Carbon dioxide fluxes and water table depth on restored formerly eroded upland blanket bog	Nearby vegetated gully	4-8 years post management	Gully blocking successfully raised water table, and revegetated sites were no longer net CO_2 emitting. Sites with revegetation combined with slope stabilisations were the highest daytime sinks of CO_2
Shuttleworth et al (2015)[123]	POC and lead losses from revegetated formerly eroding upland blanket bog	Nearby intact (no erosion) site	7-9 years post management	Reduction by two orders of magnitude, to within target levels
Green et al (2017)[124]	Vegetation composition and water table depth in drain-blocked blanket bog	No target state used, but drained areas used as control	-1 to 4 years post management	No effect of restoration treatments on vegetation or water table depth
Williamson et al (2017)[56]	Vegetation composition, aeration, and surface topography (LiDAR) in drain blocked blanket bog	No target state used, but drained areas used as control	1-5 years post management	No effect of restoration treatments on vegetation or aeration depth. LiDAR data (preceding restoration) suggest subsidence of the peat adjacent to drains, effectively leading to 'self-rewetting' without management.
Worrall et al (2007)[125]	Water colour, DOC concentration and water table depth in drain blocked blanket bog	No target state used, but drained areas used as control	-1 to 10 months post management	Water tables increased; water colour and DOC concentrations also increased, including when runoff occurred. No difference between different drain blocking techniques.
Muller et al (2015)[126]	Surface water quality in formerly afforested blanket bog	No Control area	During and up to 25 months post management	DOC, Fe, Al, Si, and PO_4 showed notable increases in concentration due to felling activities, in part likely due to mineral soil incorporation into the peat during planting.

[122] Dixon et al (2014) https://link.springer.com/article/10.1007/s10533-013-9915-4
[123] Shuttleworth et al (2015) https://onlinelibrary.wiley.com/doi/full/10.1002/esp.3645
[124] Green et al (2017) https://link.springer.com/article/10.1007/s11273-017-9545-z
[125] Worrall et al (2007) https://www.sciencedirect.com/science/article/pii/S002216940700073X
[126] Muller et al (2015) https://link.springer.com/article/10.1007/s10533-015-0162-8

Wilson et al (2011)[127]	Water table dynamics, production and transport of organic carbon and flow responses during drought and storm events in drain blocked blanket bog	No target state used, but drained areas used as control	1-4 years post management	Generally shallower water tables after drain blocking, although the reverse was sometimes observed. Flow peaks were mitigated but overall flow was more stable in blocked drains. Decreased colour and POC release due to restoration, Proportion of time at peak flow reduced, less flashy response and better retention of rainfall during storms.
Wallage et al (2006)[128]	DOC and water colour in drain-blocked blanket bog	Intact control and drained areas	6 years post management	Drain blocking reduced both DOC concentration and colour; although water contained proportionally more humic substances than in control
Stimson et al (2017)[129]	Water colour, DOC and nutrient concentrations in former eroded areas, restored by liming and fertiliser and seeding with grass	No target state, but bare areas used as control	2-4 years post management	Initial liming causes short increase in Ca; K and PO4 concentrations (substantial proportion of applied amount); no long-term change in DOC, but short-term suppression after treatment application was observed.
Holden et al (2017)[130]	Discharge, overland flow, surface flow and water table depth in drained, dammed or reprofiled former drains in blanket bog	No target state, but drained areas used as control	-6 months to 4years+ post management	Initial changes after management were a 5-fold reduction in discharge, and concomitant diversion towards overland flow and other, e.g. inter-ditch flow pathways. After more than 1 year post management, discharge in the blocked drains increased again, although not to pre-management levels. Overland flow and flow in the peat surface between ditches happened more than 50% of the time after management. Effects on water tables were small.
Holden et al; (2011)[131]	Water table dynamics in drain-blocked blanket bog	Intact control and drained area used as target and reference controls	6-7.5 years post management	Water table depth of blocked drains was higher than that in unrestored sites but not yet as high an in the control. Other responses in the water table variability were also intermediate in the restored site.

[127] Wilson et al (2011) https://www.sciencedirect.com/science/article/pii/S0048969711002099
[128] Wallage et al (2006) https://www.sciencedirect.com/science/article/pii/S0048969706001215
[129] Stimson et al (2017) https://www.sciencedirect.com/science/article/pii/S0883292717302743?via%3Dihub
[130] Holden et al (2017) https://onlinelibrary.wiley.com/doi/full/10.1002/hyp.11031
[131] Holden et al (2011) https://www.sciencedirect.com/science/article/pii/S0022169411001703

Green et al (2018)[132]	CO_2 and CH_4 fluxes and water table depth in former drains in drain-blocked/reprofiled blanket bog	No target state, drained ditches as control	Up to 4 years post management	No consistent effects of restoration on emissions from ditches. No evidence of a methane spike post restoration.
Evans et al (2018)[133]	Fluvial carbon export on a drain-blocked (2 treatments: damming and reprofiling) blanket bog	No target state; BACI[134] design within the same catchment	-5 months to 4 years post management	Both rewetting treatments increased the water table, with the reprofiling method possibly more successful. Ditch blocking may, however, have contributed to increases in run-off bypassing the ditches or overland flow. There was no effect on ditch, porewater or overland flow DOC, POC, or dissolved gases concentrations by the treatments.
Wilson et al (2010)[135]	Water table depth and surface water occurrence in 4 ditch-blocked (heather bale and peat) blanket bog sub-catchments	No target state; Before-and-after design, sequential sampling	Up to 2 years prior to, and up to 3 years post management	Water tables were higher and more stable following ditch-blocking both within drains and in adjacent peat horizons. Differences of responses were observed that relate to distance and the spatial relationship (downstream/upstream) to dam location. There was an increase of surface water occurrence due to drain blocking, both within and near drains. Average drain and stream discharge rates were lower after drain blocking, however flow variability did not consistently change.
Wilson et al (2011b)[136]	Water table depths, and ditch/stream flow during drought and storm events in 4 ditch-blocked (heather bale) blanket bog sub-catchments	No target state; Before-and-after design, sequential sampling	-2 years to +3 years post management	Water table depths at 0.5-5 m from drains were more resilient during droughts. Flow rates in the drains also remained higher and steadier during droughts. Flow-weighted total colour and DOC in drains declined but there was no response in streams. During storms, peak water table depths increased due to drain blocking. Peak flow rates in drains declined, while base rates remained stable. Decreases in total runoff caused a lower runoff:baseflow ratio. Lag times did not change, however flashiness and efficiency were reduced. Stream events were less responsive but showed similar trends except that no change in efficiency was observed.
Carroll et al (2011)[137]	Cranefly emergence in 4 ditch-blocked (heather bale) blanket bog sub-catchments and two	No target state, drained sites as control	Up to 4 years post management (dependent on site	Cranefly abundance increased with soil moisture, which in turn was increased when drains were blocked (but only in the drier of the 2 years of monitoring).

132 Green et al (2018) https://link.springer.com/article/10.1007/s11104-017-3543-z
133 Evans et al (2018) https://onlinelibrary.wiley.com/doi/pdf/10.1002/hyp.13158
134 BACI – Before-after-control-intervention
135 Wilson et al (2010) https://www.sciencedirect.com/science/article/pii/S0022169410004816
136 Wilson et al (2011b) https://www.sciencedirect.com/science/article/pii/S0022169411002915
137 Carroll et al (2011) https://onlinelibrary.wiley.com/doi/full/10.1111/j.1365-2486.2011.02416.x

	additional ditch-blocked blanket bog sites		location, 2 years of monitoring)	
Hambley et al (2019)[138]	CO_2 fluxes from formerly afforested blanket bog	Intact (undrained, unplanted) control	Two sites;10 and 16 years post management	The intact target state site was a net CO_2 sink, as was the older restored site. The younger restoration site was still a net CO_2 source.
Eastwood et al (2016)[139]				
PhD theses				
Pravia (2018)[140]	Arthropod assemblages in formerly afforested blanket bog	Local undamaged blanket bog controls	0-18 years post restoration	Trajectories were towards recovery but showed that typical bog assemblages are yet to be achieved due to persistence of generalists, as well as absence of bog specialists, in part due to habitat microstructures and microclimates not yet having been reinstated.
Hermans (2018)[141]	Greenhouse gas fluxes on formerly afforested blanket bog	Local undamaged blanket bog	0-18 years post restoration	Decreasing CO_2 losses from peat respiration following restoration, increases in CH_4 emissions with restoration age and net N_2O fixation at all sites.
Pan (2017)[142]	Carbon dioxide and methane fluxes on a former arable site (rewetted by ditch blocking and replanted) on fen peat	Nearby near-natural fen	15-17 years post management	Lower carbon dioxide fluxes at the near-natural fen than from arable fen sites, however still a net source of both CO_2 and CH_4. The near natural fen was a net CO_2 source in one year, and a net sink in the other two years.
Brown (2017)[143]	CO_2 and CH_4 fluxes from rewetted cutover and grassland peat sites	No target state for the cutover site, grassland sites compared with adjacent	0-4 months post management (cutover site) and 23-25 years post management	Water table depth effects on methane emissions dependent on vegetation (higher on rewetted vegetated ground, but low on bare peat). Rewetting reduced CO_2 emissions with the rewetted grassland being a stronger sink than the net emitting drained grassland, however the rewetted site emitted methane. This was not, however, enough to offset the net CO_2 uptake.

[138] Hambley et al (2019) http://mires-and-peat.net/pages/volumes/map23/map2305.php
[139] Eastwood et al (2016) https://www.sciencedirect.com/science/article/abs/pii/S2212041615300644
[140] Pravia (2018) https://ethos.bl.uk/OrderDetails.do?did=8&uin=uk.bl.ethos.767340
[141] Hermans (2018) https://ethos.bl.uk/OrderDetails.do?did=1&uin=uk.bl.ethos.743273
[142] Pan (2018) https://ethos.bl.uk/OrderDetails.do?did=11&uin=uk.bl.ethos.718703
[143] Brown (2017) https://ethos.bl.uk/OrderDetails.do?did=23&uin=uk.bl.ethos.742495

		drained grassland	(grassland site)	
Gatis (2015)[144]	CO_2 fluxes from drains in a rewetted Molinia-dominated bog	Paired control site	-1 to 2 years post management	No significant and consistent effect on water tables and CO_2 fluxes, however the study highlights data were collected during a climatically extreme period
Dooling (2014)[145]	CO_2 and CH_4 fluxes on rewetted, formerly cutover bog	No target state used, but unrestored area as control	4-15 years post management	Higher methane fluxes at older restoration sites, Higher carbon dioxide emissions at older rewetted sites than at unrestored control.
Sheridan (2008)[146]	Vegetation responses on a formerly afforested blanket bog (immature plantation)	Nearby unplanted blanket bog	0-5 years post management	Encouraging trajectory towards blanket bog vegetation

[144] Gatis (2015) https://ethos.bl.uk/OrderDetails.do?did=46&uin=uk.bl.ethos.666364
[145] Dooling (2014) https://ethos.bl.uk/OrderDetails.do?did=70&uin=uk.bl.ethos.644978
[146] Sheridan (2008) https://theses.ncl.ac.uk/dspace/bitstream/10443/1586/1/Sheridan%2c%20S%2008.pdf