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Peatland Restoration

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Summary

The focus of this review paper is on peatland restoration, in particular what are the policies, present drivers and examples of best practice within the UK. The aim is to review opportunities and constraints to peatland restoration and make recommendations which could be used to inform future policy.

Peatlands are wetlands in which restoration typically has three main aims. Firstly, to manage vegetation more effectively to restore sites and their conservation features to favourable condition; secondly, where feasible, to restore peat formation; and finally appropriate management of water (chiefly peat wetness, but also water quality, runoff volume and timing) Vegetation management occurs on a continuum from the vegetation of bare peat, to projects aimed at restoring appropriate plant community composition. In UK peatlands, targets for restoration have largely focused on achieving favourable nature conservation status on protected sites. In recent years, with the involvement of water companies and the movement up the political agenda of peatlands as potential carbon stores, attention has focused on large area restoration projects in the uplands. Results suggest that rewetting has been achieved by the blocking of 1000s of kilometres of drainage ditches. Considerable gains to biodiversity and reductions in carbon loss have been made over large areas by reduction in grazing animal stock densities and removal of burning management. In upland and lowland peatlands, successful restoration following tree removal has been achieved where it has been possible to return the hydrological dynamics to the pre-plantation state. However in many afforested, drained and burnt over sites, oxidation and compression of surface peat layers has resulted in changes in hydrological function, increasing the risk of invasion from undesirable plant species and the loss of *Sphagna*.

A major problem limiting what we know about the success of peatland restoration is the absence of long-term monitoring data. Post restoration monitoring shows that recovery of water levels is possible in a relatively short time frame (2-5 years) Many restoration projects show short term negative impacts on surface water quality and methane generation but, where data exist, positive responses in the medium to long term. Restoration of target mire vegetation in response to management may take several decades to achieve with agriculturally improved and heather dominated peatlands presenting the greatest challenges. Restoring appropriate *Sphagnum* species and cotton grasses is vital to restoring peat forming processes and securing UK peatlands as both secure long-term stores of carbon and also future carbon sinks.

In addition to the literature, this review draws upon information gathered from the Peat Compendium and workshops involving expert consultees, which were carried out as part of the review. During workshops there was a great deal of consensus on what could and could not be achieved using existing restoration techniques. Also presented within the paper are a series of knowledge gaps and uncertainties. An important point of agreement was that the most convincing argument for the funding of future restoration projects could be made using the multiple objectives of carbon sequestration, water management and biodiversity gain. However a significant future challenge is to understand how various climate scenarios, such as increased temperatures, summer droughts and higher intensity rainfall events are likely to affect peatlands. In particular it was agreed that the lowering of mean water tables and oxidation of peat are likely to result in increased growth and competition from vascular plants which, in marginal climatic zones for peat formation, could make restoration to our current target concept of blanket or raised bog difficult. A further significant point of agreement was the need to restore

peat bogs to make them more resilient to climate change, to reduce rates of loss of biodiversity and carbon and to reduce loss of peat into water bodies.

Key summary points

- Peatland restoration projects need to be clear about their aims. In peat bogs where carbon sequestration is a principal aim of restoration works, achieving a surface cover rich in *Sphagna* and cotton grasses (*Eriophorum* sp.) should be the ultimate and quantifiable objective.
- Methods for restoration of *Sphagna* rich surface layers require further development and evaluation in order to produce best practice guidance.
- On severely damaged /modified peatlands, funding needs to be available for phased restoration. Some form of monitoring should be made a requirement of funding.
- Managed burning and restoration of surface rich *Sphagnum* layers on deep peat are probably not compatible.
- Research is required on the impacts of grazing and trampling on active peatland.
- Tried and tested methods have now been developed for the rewetting and revegetation of peatland from past drainage and methods are being developed for rewetting gullied systems.
- In eroded peatland systems restoration is an effective measure to avoid further loss of peat and carbon. The evidence also suggests that peatland restoration is an effective means of enhancing carbon sequestration on less degraded sites. Peatland restoration as a potential carbon offsetting measure should be explored.
- A national peatland restoration strategy is needed to provide a context for the many local/regional projects planned or underway and to stimulate further bids and funding structures.
- Government targets need to be agreed for the restoration of areas of active peat. Assessments could be a carried out as part of a modification of common standard monitoring.
- Funding should be sought for regional research coordinators to carry out a UK wide co-ordinated and integrated meta-data analysis with the aim of producing best practice guidance on monitoring and peatland restoration methods.
- Funding is required for a web-based forum, such as the Peat Compendium, with regional coordinators, acting as trainers and facilitators of best practice.
- The strongest case can be made for the restoration of peatlands when using the multiple objectives of an ecosystems services approach.

1. Introduction – Aims, Scope and Objectives of Review

This paper forms part of a series of technical reviews, commissioned by the IUCN UK Peatland Programme and is aimed at assessing the evidence for the efficacy of the different peatland restoration techniques or approaches. In addition to peer-reviewed and 'grey' literature this review draws upon information gathered from the Peat Compendium (Holden *et al* 2009) and workshops involving expert consultees, which were carried out as part of this review. Section 1 provides definitions and outlines the significance of UK peatlands. Section 2 highlights the main causes of peatland degradation. Section 3 outlines the main drivers and aims of peatland restoration. Section 4 describes the current restoration methods. Section 5 provides an evaluation of restoration practice and evidence for success. Section 6 discusses the major challenges, different approaches to monitoring and considerations in relation to climate change and makes recommendations.

Projects involving the restoration of disturbed and degraded peatland have been on going in the UK for over 30 years (Wheeler and Shaw 1995; Anderson *et al* 1997; Brooks and Stoneman, 1997)) Restoration can be defined as "the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed" (SER International Science and Policy Working Group, 2004) The challenge presented by this review is that the scientific understanding of restoration and the mechanisms by which ecosystems provide us with services lags behind the implementation of restoration measures (O'Brien *et al* 2007)

1.1 Definitions and scope

There are three main types of peatland (defined for the purpose of this review as peat greater than 40cm deep) in the UK: lowland fens, blanket bog and valley mire and raised bog (upland and lowland) Raised bog and blanket bog, represent by far the largest area of deep peat in the UK. There are three bog pool National Vegetation Classification (NVC) communities associated with blanket bog – M1, M2 and M3. In addition there are seven NVC mire vegetation types on deep peat – M15, M16, M17, M18, M19, M20, and M25. Four of which (M15, M19, M20 and M25) represent degraded examples of blanket bog. There are two NVC dry heath vegetation types H9 and H12 and one NVC grassland type (U6), found on deep peat which are also degraded examples of blanket bog (Rodwell *et al* 1991, Natural England/Moors for the Future (in prep)) All of the intact communities M1-M3 and M16-M18 are considered a priority under the EU Habitats and Species Directive (92/43/EEC) Please consult IUCN Topic 3 for further details.

In simple terms all peatlands can be classified as 'active' or 'non-active'. The term 'active' in the sense of the Habitats Directive definition (Natural England 2008), is used to describe a peatland which "still supports a significant area of vegetation which is normally peat-forming" and is therefore assumed to be actively laying down peat (JNCC 2006) It should also be noted that "active" peat forming communities exist on layers of peat thinner than the 40cm definition.

Active peat bodies are regarded classically as consisting of two layers; a relatively shallow surface layer of periodically aerated, highly conductive peat with a fluctuating water table (the acrotelm), which overlies an 'inert' deeper layer consisting of permanently water logged, anaerobic peat (Holden and Burt 2003) There has been concern over the extent to which peatlands in the UK have lost their protective acrotelm and therefore represent 'non 'active' systems as a result of human action (Lindsay 2010)

Lowland fens and valley mires occur typically in basins and hollows which receive considerable inputs of water from the surrounding land (minerotrophic) and where drainage is impeded (Brooks and Stoneman 1997) There is a well developed literature on the importance of achieving appropriate water levels and quality of receiving waters (Meade 1992; Wheeler and Shaw 1995; Holden and Burt 2003; O'Brien et al 2007) There have been many successful restoration projects in the lowlands, like the great fens project, where gains to wildlife have been significant.

In terms of the area of peatland presently undergoing restoration in the UK, blanket bog accounts for over 75% of the total area (Holden *et al* 2008a) As a result of this and the overwhelming contribution that blanket bog makes to the total UK peatlands this review is concentrated on the results of restoration measures carried out on blanket bog. Blanket bog is defined as a peatland which is not confined by the surrounding topography and is extensively rain-fed (ombrotrophic) with little or no contribution from laterally moving mineral-rich soil waters. It is also one of the most extensive semi-natural habitats in the UK and ranges from Devon in the south to Shetland in the north (Van der Wal *et al* 2011) There are many opportunities for landscape scale restoration projects in the uplands, where land values are typically low and there are less severe levels of peat loss and degradation from the reduced intensity of agricultural (Natural England 2010a)

Lowland peats (lowland fens and raised bogs) in the UK are much less extensive and generally fragmented by intensive agriculture. They are nevertheless extremely rare and important habitats whose conservation and restoration is of national and international concern (Brooks and Stoneman 1997) The common causes of degradation for upland and lowland peatlands are often different (Williams 2006) but the restoration techniques and knowledge gaps are similar at least for lowland raised bog. This review provides limited specific information on the restoration of lowland fens. Please see extensive reports by Wheeler *et al* (2002), Scottish Natural Heritage (2010) and Northern Ireland Environment Agency (2010)

2. Levels of Peatland Modification and Damage

Peatlands can be modified or damaged in a number of ways and to varying degrees. The main drivers of change have been grazing, managed burning (Muirburns), wildfire, atmospheric deposition, drainage, agriculture, afforestation, peat extraction and recreation (Tallis 1998) Damage can also be attributed to various developments on peat such as estate tracks, wind farms, quarries and other developments. Of these factors, grazing and managed burning are the most widespread and where too intensive and regular over a long period, can alter the vegetation in favour of species such as *Molinia caerulea* and *Calluna vulgaris* with associated reductions in the cover of *Sphagnum*. Such management can alter the 'natural' hydrology through the loss of *Sphagna*, resulting in lowered water tables and the loss of microtopography and patterning (Tallis 1998, Evans *et al* 1999, Holden 2008b) Drainage of peat, particularly blanket peat, was undertaken extensively in the mid 1900s (known in the English uplands as gripping) with Government grants continuing until the 1980s, with the aim of increasing heather and grass cover to support more sheep. Drains allow the rapid diversion of water off site by intercepting overland flow and increasing drainage density, and have been linked to increased risk of downsteam flooding. There is clear evidence of reduced water tables within a few metres of drains (Stewart and Lance 1991) It has also been argued that drainage can lead to larger scale zones of water table drawdown (i.e. tens of metres), particularly where underlying permeable material such as sand has extended the zone of influence (Schouten 2002, JNCC

Hydrological Protection Zone model, Richard Lindsay 2010) Drainage can result in significant drying of the peat where drains are dense and is particular significant as changes in the water table of just a few centimetres can have a dramatic effect on bog vegetation (Brooks and Stoneman 1997, Robroek *et al* 2006)

In the 2006 assessment of the condition of upland peats (on SSSIs) in England, the three most common damaging activities were found to be over-grazing, managed burning and drainage (Williams 2006) Where wildfires occur, then serious damage can be caused to that particular location (Maltby *et al* 1990, Yeloff 2006) In the worst cases, it can result in complete loss of vegetation with bare and eroding peat on a small to very large scale (Tallis 1997, Phillips *et al* 1981, Evans and Warburton 2007, Carroll *et al* 2009) Bare peat is an ongoing state which affects 4000ha of blanket bog peat in England alone (Natural England 2010a) If this persists over a long period, peat can be completely lost and mineral ground exposed. Areas of eroding peat are particularly extensive in the Peak District, South Pennines, south Wales and southern Scotland where they are often occur close to urban areas with (in the past) high aerial deposition of sulphur dioxide. In these areas the effects of atmospheric pollution has added to the impacts of wildfire, over-grazing and managed burning. The products of this past pollution, in parts of the Peak District, is believed to be one of the key factors preventing regeneration of vegetation on bare peat (Caporn *et al* 2009) Much of the effects, for example in the Peak District, are down to 'historic' pollution from Victorian times where aerial deposition of sulphur dioxides has cause the peat surface to become more acidic, resulting in hydrogen and metal ion phytotoxicity. While 'critical loads' of atmospheric nitrogen and acidity are currently being widely exceeded across the uplands, any effects on vegetation are believed to be secondary.

In an active peat bog, typically only 10% of the annual primary plant production is laid down as peat, with on average 0.5-1mm increase in the depth per annum over deep peat (Tallis 1998) *Sphagnum* and in particular terrestrial species such as *S. papillosum* and *S. magellanicum* have recalcitrant tissues with high C:N and P:N ratios. Compared to vascular-plant species *Sphagna* are slow to decay and in most peat bogs are responsible for laying down the majority of the accumulated peat (Daniels and Eddy 1985)

Please consult IUCN review Topic 1 for further information on the 'state of peatlands'.

Figure 1 illustrates a typical spectrum of degradation from intact active peat bog to dry, usually *Molinia, Eriophorum* or heather-dominated dwarf shrub habitat. The degraded peat bog transforms into a relatively stable semi-natural vegetation community, where the rate of peat wastage is often relatively slow, and which may support features of nature conservation interest (Tallis 1998, Pearce-Higgins *et al* 2009) These semi-natural vegetation types provide many environmental goods such as water, wildlife interest and agricultural products (most commonly livestock), but will not act as significant carbon sinks without the restoration of a stable, near surface level water table. Depending on the degree of drying, they may be appropriate holding points for our peat reserves, but more typically are likely to be net sources of green house gases (GHG), due to slow rates of peat mineralisation.

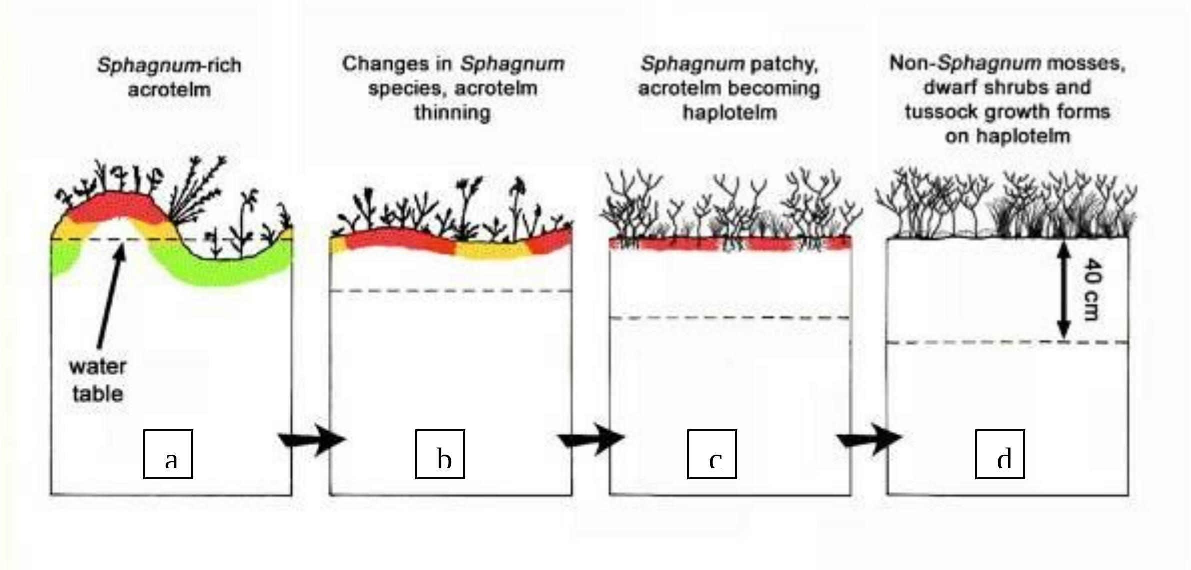

Figure 1 *Effects of a lowering water table on vegetation close to a drain/gully. a) pool and hummock structure of an intact active peat bog. b) drawdown of water table with loss of pool. c) Increase in dwarf shrubs and grasses. d) loss of Sphagnum and functioning acrotelm layer. Reproduced with permission of Richard Lindsay (Lindsay 2010)*

Figure 2 shows the influences of drainage channels or ditches cut though active peat bogs which cause large areas of the down slope surface of the acrotelm layer to be emptied of water. Subsequent falls in the water table of only 10cm can have a dramatic effect on the vegetation causing a switch from *Sphagnum* dominated vegetation to dwarf shrubs and grasses (Tallis 1998, Evans *et al* 1999, Charman 2002, Robroek *et al* 2006) Peat is formed in the acrotelm, largely by *Sphagnum* and *Eriophorum*. Drainage results in death of the *Sphagnum* and the functioning acrotelm and the peat bog looses its ability to sequester carbon (Wheeler and Shaw 1995, Schumann and Joosten 2008) Vascular-plant species come to dominate the surface layers of the blanket peat which are more readily decomposed and therefore provide little or no net long-term carbon sequestration.

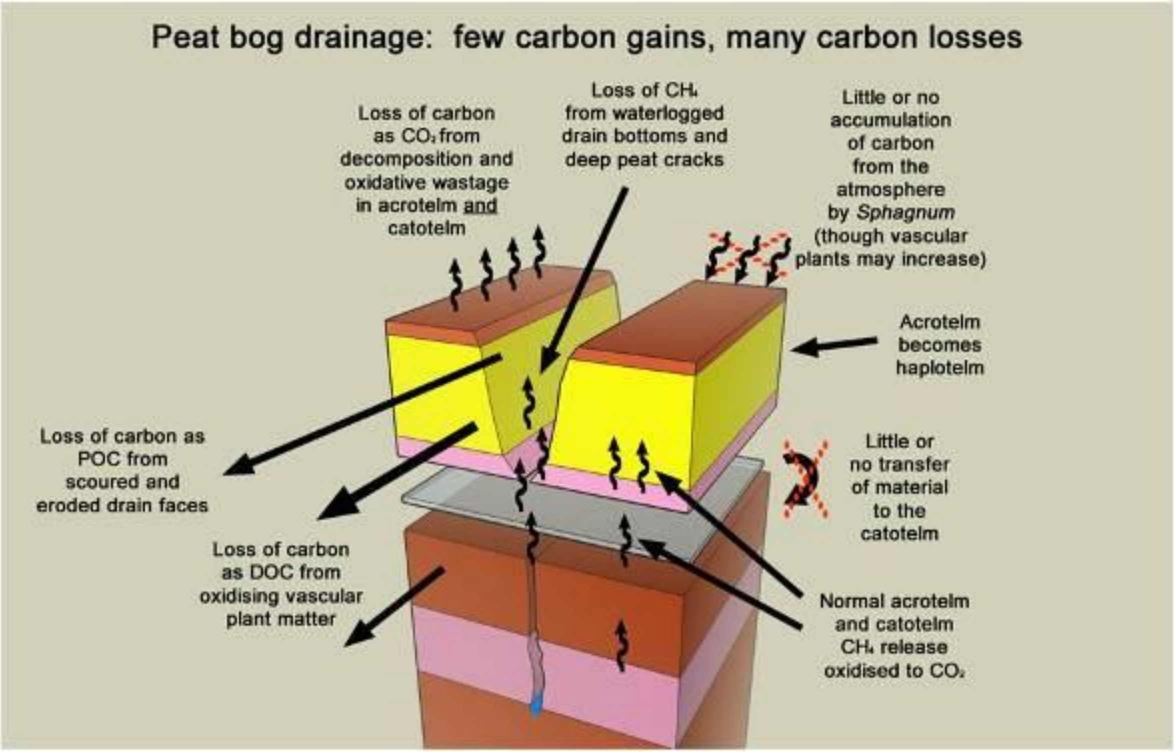

***Figure 2** Cross section of a degraded blanket bog illustrating carbon losses from an eroding drainage channel or gully. Falling water levels cause oxidative wastage of peat and loss of carbon. Increase in vascular plants and decline of Sphagnum from the acrotelm removes annual inputs of plant litter to the catotelm. Peat decomposition and scour release particulate organic carbon (POC) from the acrotelm layer and dissolved organic matter (DOC) is released as the products of partial decomposition. Reproduced with permission of Richard Lindsay (Lindsay 2010)*

2.1 Extent and location of areas requiring restoration

There is an estimated 22,500km^2 of blanket peat in the British Isles of which only approximately 4000km^2 is in a near-natural state (Tallis 1998) Around 74% of England's deep peatlands show visible peat degradation * or are subject to damaging land management practices** (Natural England 2010a) Including damage from pollution this figure reaches 96%.

* Includes hagging (whale backs of standing peat) and gullies, bare peat and peat wastage.
** Includes cultivation, agricultural improvement, drainage of peatlands, managed burning, overgrazing, afforestation, peat extraction and old peat cutting.

Degraded deep peats (upland and lowland) often support semi-natural communities dominated by tussock-forming graminoids, dwarf shrubs (particularly *Calluna vulgaris*) and scrub woodland as well as *Sphagnum*-devoid wet heath (Tallis 1998) An additional 1.5 million ha^{-1} of deep peat, in the UK, has have been afforested or under cultivation (Natural England 2010a) Recent changes in planting regimes and policies by the Forestry Commission have reduced the threat from afforestation and present significant potential for future peatland restoration (Anderson 2010; McAllister 2009) Figure 3 illustrates the relationship between categories of active and degraded peat and suggests that it is possible, although more difficult in some cases, to restore all of these to an active peat-forming state once the degrading influence(s) have been fully removed. In Scotland and Wales in particular the construction of wind farms represents a potential future threat to blanket bog (Dargie 2008, Drew 2010) Environmental impact assessments are required for all developments with five or more turbines (Dargie 2008, Natural England 2010b) However there is still significant concern regarding the adequacy of mitigation measures, such as the rafting of access tracks over deep peat and the impacts of dewatering and sedimentation during the construction of turbine bases (Grieve and Gilvear 2008, Natural England 2010b, Drew, 2010) Windfarm developments on peat are an ongoing area of concern which require effective mitigation and restoration measures and where adequate mitigation is not possible an acceptance of peat as a genuine constraint in the planning process.

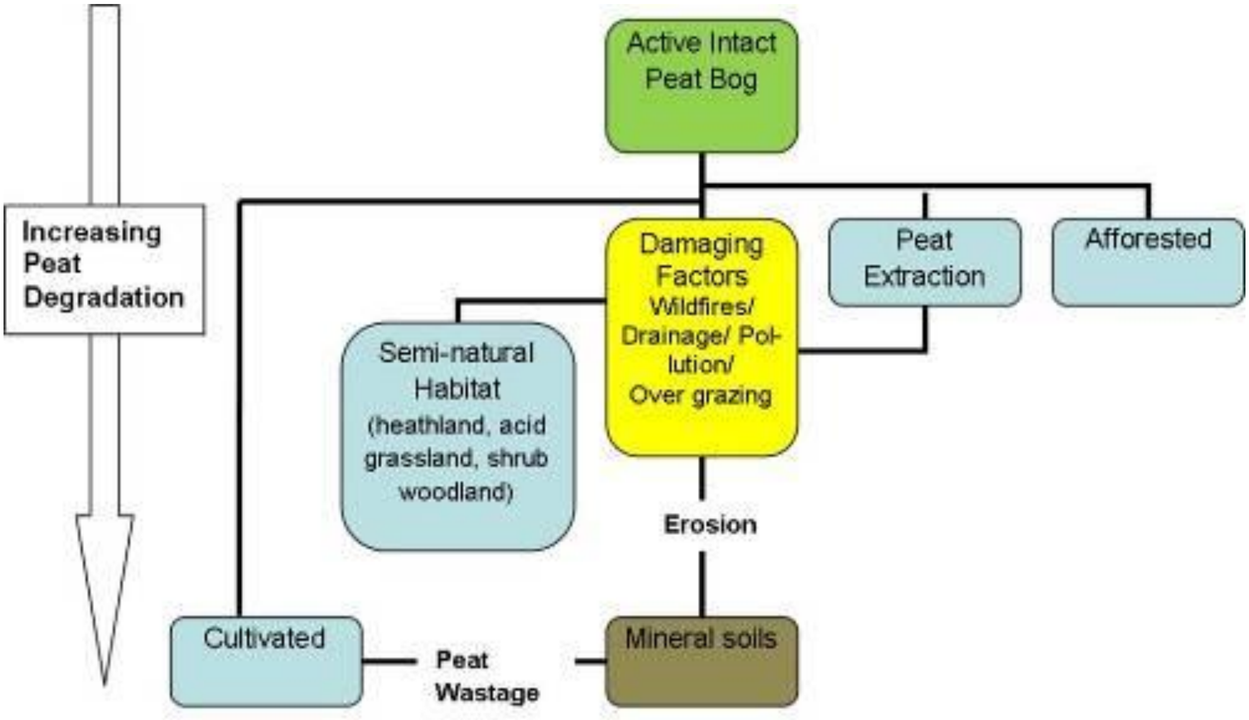

Figure 3 *Intensity and causes of peatland degradation This diagram illustrates the degradation from active peat bog with a peat forming acrotelm layer to other land use states. The gradient represents one of increasing difficulty, time and costs to restore*

3. Drivers of Peatland Restoration

The key objective for restoring peatlands should be to re-establish vegetation commensurate with active peat formation. The means of achieving this is through re-vegetation, if there is none, vegetation manipulation and/or hydrological restoration. Since the early 1990s securing favourable nature conservation status of national (SSSI and BAP) and international (EU Habitats and Birds Directives) species and habitats has been a major driver for peatland restoration works; in particular the control of burning and management of animal stock densities to prevent over grazing. In England around 2/3rds of the blanket bog has been notified as SSSI, only 11.4% of which is in a favourable condition (Williams 2006) In Scotland the majority of peat bog (including active peat bog) does not lie within designated sites and therefore is not subject to regular condition assessments.

In England restoration is mainly being funded by Natural England more recently through agri-environment schemes (Higher Level Stewardship and Environmentally Sensitive Areas) and Tir Gofal in Wales to achieve Public Service Agreement targets for SSSI condition. These funding schemes did not, in general, seek to restore the hydrology or active peat forming processes. During the last ten years water quality and more recently water quantity have become drivers for intensive localised catchment based restoration work (e.g. UU SCaMP Box 2) This work has been driven by water companies in an effort to reduce the costs of treating raw drinking water quality in an environment where DOC levels were rising steadily (SCaMP 2010) Findings from the Peat Compendium (Holden *et al* 2008a) suggest an apparent mismatch between reported aims and outcomes. Nature conservation was the most widely cited justification for peatland restoration with the greatest expenditure on monitoring but the area where the least significant improvement was reported. Similarly carbon sequestration was considered a justification for 62% of restoration projects with, in most cases, an absence of any effective measures to restore a *Sphagnum* rich surface layer.

The main change over the last five years has been greater integration of many of these objectives and the recognition that these wetland areas are multifunctional. Ecosystem services (Natural England 2009a) have emerged as a key driver of these new integrated management systems. Peatlands are recognised as providing many ecosystem services including biodiversity, agricultural products (sheep, cattle and vegetables), forestry, water resources, flood water retention, recreation (predominantly walking, shooting and mountain biking), archaeological resource and landscape enhancement. The most recent drivers and ones increasingly recognized by government are carbon sequestration (Defra 2006; Bonn *et al* 2010) and flood control. Agreement reached at UNFCCC conference in Copenhagen (2009) in the category of Landuse, Land-Use Change and Forestry (LULUCF), could eventually allow nations to include peatland restoration in their greenhouse gas accounting. Presently agreement is pending over the inclusion of wetland restoration as an elective activity under the Kyoto Protocol. In the future this agreement could enable peatland land managers, particularly in the uplands, to gain financially from appropriate management and restoration of peatlands (Natural England 2009b) For extensive reviews of the ecosystem services provided by peatlands please consult Immirzi (1997), Defra (2006), Parish *et al (*2008), Natural England (2009b) and Bonn *et al* (2010)

Please consult IUCN review Topic 7 ‘peatland policy’ for further information.

4. Outlines of Peatland Restoration Methods

Peatland restoration methods can be divided into three main categories: water management (defined here as ditch or gully blocking), re-vegetation and vegetation management. It is recognised that the general term “rewetting” as proposed under LULUCF discussions could potentially embrace all three categories. The principal aims of these methods are to restore vegetation cover (on bare and eroding peat), hydrological function and active peat forming vegetation.

Techniques for restoring areas of bare peat have been extensively tested in The Peak District and the Pennines (a team based at Manchester University plus Penny Anderson Associates, Anderson *et al* 1997, Anderson *et al* 2009) Moors for the Future has taken many of the techniques trialled and scaled them up for large scale works and taken forward new methods for restoring severely damaged blanket peat in the South Pennines and Peak District. The work in the Peak District has been successful in re-vegetating bare peat. This, along with ditch blocking, is only the first phase in restoration to active blanket bog. Phase 2 involves the restoration of an active peat forming mire vegetation (Table 4.1) Much of the successful peatland restoration work has involved the use of Phase 1 methods (Table 4.1) There is still much work to be done on validation of the efficacy of the Phase 2 methodologies (Table 4.1)

Sections 4.1-4.3 provide a summary description of the most commonly used peatland restoration techniques.

4.1 Water Management

Water management techniques for lowland and upland peatlands most often involve a process known as rewetting (Brooks and Stoneman 1997; O'Brien *et al* 2007) This is where introduced drainage ditches (grips) or eroding features of the dendritic stream system (gullies) are blocked to allow water levels within the peat to return to their 'natural' levels, as far as is possible. These 'natural' water levels are closer to the peat surface and show less seasonal fluctuation. The success of rewetting following ditch blocking has been much greater than that reported, so far, for blocking deeper gullies.

- Ditch Blocking

The standard method of blocking makes use of peat scooped up from areas in or adjacent to the ditch and packed as a plug into the ditch with the vegetation surface upper most (Worrall *et al* 2007) Plastic, wood, heather bales and plywood have also been used to block ditches and gullies but may be more intrusive and are expensive; different materials suit different slopes and water flows. Particularly large ditches may be blocked using both peat and plastic for support. By blocking with peat at regular intervals along the ditch, water can generally be diverted out of the ditch and onto the peat surface (Figure 4) Ditch re-profiling is sometimes also needed where the cross section has become flask-shaped. There is now sufficient experience to be able to refine the methods involved to avoid blocked ditches becoming eroded, undercut, or for them to be washed out. This is particularly pertinent on slopes.

- Gully Blocking

On damaged blanket bog peat erosion, for example after wildfires, can lead to the formation of drainage channels known as gullies. These gullies most often form on the edges of peat bodies where the contributing area and slope is greater but may also stretch across the whole peat bog. They may be small, narrow or very wide, eroded to bedrock with large quantities of peat lost from the system and large whale-backs of peat all that remains of the former bog surface. The techniques to re-wet gullied bogs focus on the blocking of smaller, narrower gullies rather than when most of the peat has been lost. The methods used to block are varied, involving the use of permeable, semi-permeable and impermeable barriers (e.g. stone, wood, peat, plastic) Local availability and the labour source (contractors, volunteers etc) are the most common determinants of the choice of material.

Evans *et al* (2005) found that the optimum height of dams was 25-45cm, maximum distance between successive dams 3m and maximum slope angle >6^{o}, although successfully blocked gullies have now exceeded these measurements (Anderson *pers. comm*.) Best practice recommends that blocks are constructed initially at the head of the gully system working down slope, thereby reducing the contributing area to subsequent blocks. Where possible, on near flat peatlands, the spacing and height of successive blocks should be such that the sill of the subsequent block is above the toe of the previous block. During periods of peak run-off this can lead to the formation of pools, which allow water flow over the sills to fall on to a water surface thereby reducing erosion and undercutting.

Gully blocks do not typically extend to the full height of the gullies. Consequently, although water tables are raised water is not diverted out of the gully system and therefore the gullies continue to act as drainage lines. Alternatively ditch blocking usually extends to the full height of the ditches and therefore potentially removes the drains as drainage lines. However, one of the problems with ditch blocking is to understand where the diverted water passes after blocking. Many damaged blanket peat areas have extensive peat pipe systems underground, either in the upper horizon of the peat body, or running along the interface with the mineral surface beneath. Holden (2009) has suggested that the peat pipes are at a greater density below peat that has been damaged through drainage or wildfires in the past and that around 10% of the water can drain through them off a site, with up to 30% in extreme circumstances. It is possible that where the density of peat piping is high that the blocking of drainage channels alone may not be fully effective in the rewetting of a site.

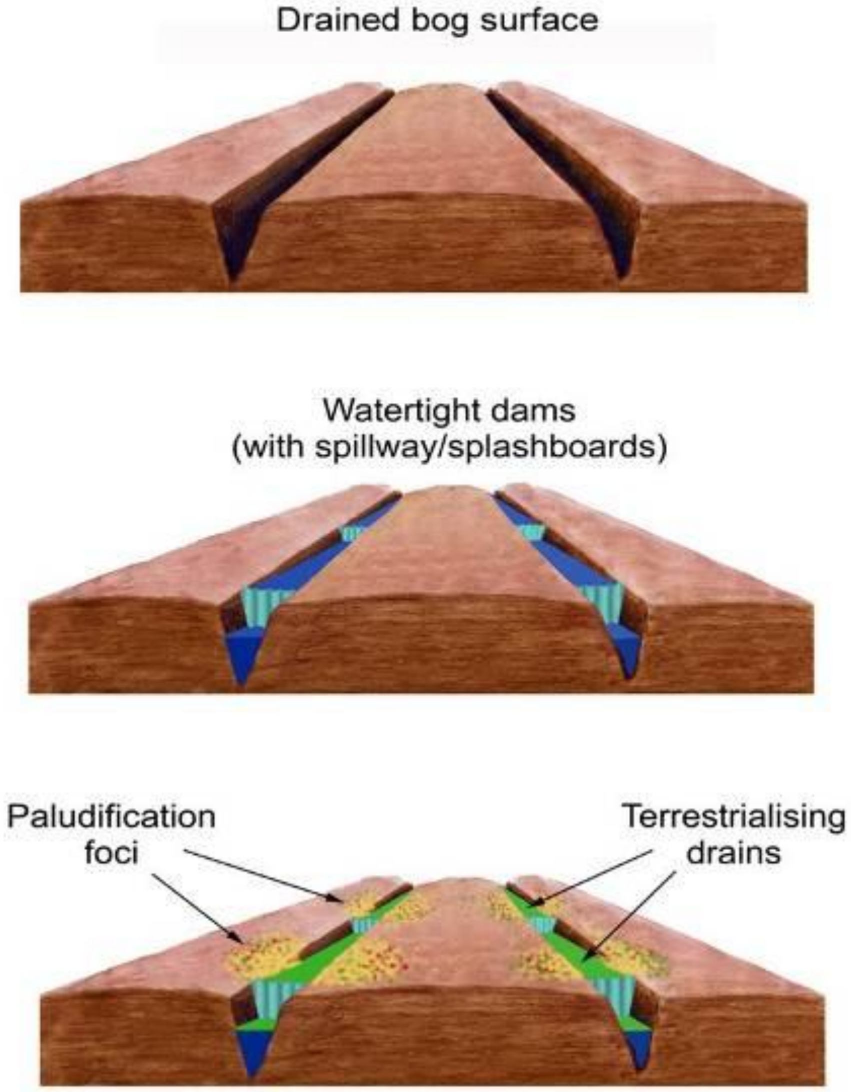

Figure 4 *Blocking of drainage ditches ;middle diagram showing pooling of water behind corrugated plastic dams; lower diagram showing rafts of Sphagnum developing over open water filled pools (terrestrialisation) and spread of cotton grasses and Sphagnum over formerly drier oxidised peat surface at margins of ditch (paludification) Reproduced with permission of Richard Lindsay (Lindsay 2010)*

4.2 Revegetation of bare peat

Revegetation is essential where extensive bare peat has formed. The principle that is applied is to identify the factors that prevent natural colonisation and address them, starting with the cheapest and easiest and working up to the complex and costly only where necessary. This may involve excluding grazing (wild and domestic stock) (Anderson and Radford 1996) If this is inadequate, the next level of intervention is to add the desired plants (e.g. through heather brash, planting divots, plug plants, seed or *Sphagnum* diaspores) In situations where peats are bare and eroding they may require stabilisation with heather brash or geojute to allow re-vegetation. In exceptional circumstances, where peats have been so badly affected by past aerial pollutants, peat surface pH typically < 3.5, chemical modification with lime and fertiliser is a prerequisite to successful establishment of vegetation. These techniques have been most extensively used to re-vegetate bare, eroding blanket peat with dwarf shrub and nurse grass seed mixes (Anderson *et al.* 1997) .

- Vegetation of bare peat with heather brash and nurse grass seed with lime and fertiliser

The target pH for restoration has been taken as a pH of greater than 3.8. Phosphorus and potassium may be added at low levels. Nitrogen, although it has been added, is not necessarily required because of high atmospheric inputs. Typical levels of inputs necessary to support nurse crops in particular, would be 1000 to 2000 kg lime ha^{-1}, and 125 kg h^{-1} NPK plus 200 kg h^{-1} of slow release, high phosphorus fertiliser (Anderson *et al.* 1997) Moors for the Future recommend even higher levels, 360kg per hectare in year 1 (40N:60P:60K) and 290kg per hectare in years 2 and 3 in order to sustain the nutrient requirements of the nurse crop (http://www.moorsforthefuture.org.uk/repairing-bare-peat) Fertilised swards have also been shown to remain attractive to stock for many years. This treatment should therefore not be used without grazing exclosure.

- Peat stabilisation using nurse crops together with geotextiles such as geojute

Expensive method used on severely eroded and sloping sites, more typically at the edge of gullies where geojute is laid in strips, where use is most commonly combined with a nurse species seed mix (see below) The geojute, fibrous mesh webs (3cm pore diameter) disintegrate with time, leaving stabilised peat surfaces.

- Peat stabilisation and introduction of heather using seed or brash

Brash is used to stabilise small patches where heather is available. This material is cut from local donor areas in the autumn when seed is still on the plant and spread over degraded recipient sites in an area up to twice as large as the donor site (area ratio 1:2)

- Planting of other blanket bog species e.g. *Eriophorum angustifolium, E. vaginatum* and *Erica tetralix*

Establishment of vegetation occurs from regrowth of vegetative fragments and from seed. *Deschampsia flexuosa*, *Agrostis castellana* (non-native grass)*, Festuca ovina* and *Lolium perenne* (not a bog species) are species typically used in the seed mixes. Stabilisation techniques have included the use of *Eriophorum vaginatum* and *Eriophorum angustifolium*, transplanted into the peat as individual shoots, small turves or plug plants as well as other species (including *Empetrum nigrum and Vaccinium spp.*) (Anderson *et al* 1997), http://www.nationaltrust.org.uk/main/w-views-peatland.pdf, http://www.moorsforthefuture.org.uk/repairing-bare-peat .)

4.3 Vegetation management

Where semi-natural or introduced vegetation is present and the objectives are to restore an active peat forming *Sphagnum* rich surface layer, steps need to be taken to remove or modify the existing vegetation.

4.3.1 Introduction of *Sphagnum*

A high and stable water table is an essential precondition for restoring a *Sphagnum* rich surface. The elimination of other degrading factors is also required such as: burning, trampling, grazing (particularly high stock density combined with supplementary feeding), a low pH (<3.5), high inputs of nitrogen and phosphate from receiving waters and/or nitrogen from atmospheric deposition.

Sphagnum restoration trials are ongoing on blanket bog in the Southern Pennines (Carroll *et al* 2009, http://www.moorsforthefuture.org.uk/repairing-bare-peat) Published results in the UK are largely confined to raised bogs using the methodology of Wheeler *et al* (1995) This method involves the inoculation of suitable areas with diaspores (vegetative *Sphagnum* fragments 0.5-2cm in size) These are spread directly on the peat or vegetation surface for lawn species (typically *S. magellanicum, S. capillifolium* and *S. papillosum*) or into pools for the aquatic species (*S. cuspidatum* and *S. fallax*) *Sphagnum* is collected from the top 10cm of a donor area. One hectare of donor site provides enough *Sphagnum* fragments to 'seed' up to 10ha of recipient area. Moors for the Future are developing *Sphagnum* propagation project investigating methods of introducing encapsulated *Sphagna* and its survival in different conditions (http://www.moorsforthefuture.org.uk/node/144)

On severely degraded upland blanket bog in the Southern Pennines the methods under investigation involve the reintroduction of *Sphagnum* along with transplants of *Eriophorum angustifolium, Erica tetralix* and *Empetrum nigrum.* This introduction is combined with nurse seed grasses, geojute to stabilise the peat and a granular lime and NPK fertiliser mix (Anderson *et al* 1997; Carroll *et al* 2009) Caporn *et al* (2007) suggests that the lime and fertiliser additions are soon dissipated and that effects of applications on blanket bog are short term. Further work is required to establish the implications of lime and fertiliser applications for *Sphagnum* introduction and microbial activity within the peat.

Restoration trials on cut over lowland peat extraction sites are presently under way (Natural England *pers. comm.)* using small raised bunds (~250mm) of undecomposed peat capped with heather brash or coir matting to construct shallow (~10cm deep) inundated cells (20x20m), which are seeded with milled *Sphagnum*. These *Sphagnum* fragments are then protected by a thin covering of fresh straw or heather brash. This cell pattern is repeated over the entire degraded area forming a series of 'paddy fields' with excess water over spilling from one cell to the next. Cost ranges from around £2500 +VAT/hectare if using in situ peat/vegetation to £4/£5k if using heather brash or coir (Alasdair Brock, Natural England pers. comm.) In Canada and the USA commercial peat extraction sites are routinely restored using the diaspore inoculation method with addition of NPK fertilisers and straw mulch. Fresh long stemmed straw is spread over the bare peat surface as a mulch, and to provide a scaffolding structure following diaspore inoculation at a rate of 3000kg/ha (Quinty and Rochefort 2003).

4.3.2 Sustainable grazing

Natural England (In prep.) recommend not more than 0.1sheep/ha all year (0.012LU/ha) or a max of 0.2sheep/ha for 6 months in summer to bring blanket bog and wet dwarf shrub heath into a favourable condition. The levels set will depend on access to other vegetation outside the peatland and their attractiveness to the stock. Shepherding, wilding or fencing is normally required to prevent grazing and trampling damage to introduced peat bog vegetation (Bayfield 1979, Anderson *et al* 1997, Studlar 1980) The removal of grazing animals from areas which have been over-grazed in the past has proved an effective first step in the recovery of bog vegetation.

4.3.3 Cessation of burning

There are several government guidance documents and research reports which state that prescribed burning on active peat bog should not occur (Coulson 1992, Sherry *et al* 2005) or that recommended a strong presumption against burning peat bog and wet heath (Glaves and Haycock 2005, Defra 2007) Agreed burning continues on degraded peat bogs, where through regular burning, heather has gained dominance. Where carried out this practice will continue to discourage *Sphagnum* and encourage the growth of tolerant vascular plants.

- Heather and *Molinia* reversion

Monocultures of perennial tussock forming *Molinia* occur over large areas of damaged deep peat in both upland and lowland areas of the UK. According to Anderson *et al* (2009) restoration to revert these monocultures into active peat forming vegetation requires the removal of the competing vegetation followed by the introduction of the mire community. Options for removal of the existing vegetation include use of herbicides and burning followed by grazing of regrowth by cattle, on *Molinia* dominated areas. These techniques have been used successfully to revert *Molinia* to a more diverse dwarf shrub vegetation, usually dominated by heather.

On deep peats dominated by heather or *Molinia* it is unlikely that one technique alone will achieve the desired result. Restoration techniques are rarely used in isolation; most sites have a range of degrading influences which require multiple measures to achieve a target of active peat bog. In the case of *Molinia* or heather reversion it is possible that vegetation removal followed, where possible, by water management and mire species introduction would prove the most successful. However these combined techniques require further investigation.

4.3.4 Removal of scrub and woodland

An estimated 3,500km^2 of British blanket mire is afforested (Tallis 1998) Works done by the Forestry Commission include the large-scale clear fell of conifer for peatland restoration. The brash is often left in rows and used as bog mats to support the felling and extraction machines (McAllister 2009, Anderson 2010) In some cases trees are flailed to waste leaving significant debris remaining on the bog surface. On lowland raised bogs, where funds allow, to reduce nutrient pools tree brash is often removed from site or burnt on galvanised sheets with ash being removed (Brooks and Stoneman 1997) Grab lines have also been used to avoid further compaction and disturbance of the peat from harvesting equipment. On smaller sites hand pulling of seedlings is used to control birch, willow and conifer regrowth. Clear felling is usually accompanied by rewetting via ditch blocking (Section 4.1) Drainage ditches and plough furrows are normally in filled with on site materials such as peat or tree brash using low ground pressure excavators (McAllister, 2009, Anderson 2010)

Table 1 *Peatland Restoration Best Practice Guidance*

Restoration Technique	**Guidance Document**
Phase 1	
Ditch/Grip Blocking	Holden (2009) A grip blocking overview. Report for the Environment Agency. Project 30254994. Armstrong *et al* (2009) Drain-blocking techniques on blanket peat: a framework for best practice. Journal of Environmental Management, 90, 3512-2519. Natural England and Moors for the Future (In Prep.) Moorland Restoration Handbook
Revegetation of Bare Peat	Buckler *et al* (2007) Bare peat restoration on Peak District moorlands. Moors for the Future Research Report No. 14. www.moorsforthefuture.org.uk. Natural England and Moors for the Future (In Prep.) Moorland Restoration Handbook. Anderson *et al* (1997) *Moorland management Project, Phase III Report,* Peak Park Joint Planning Board, Bakewell. Anderson *et al* (2009) Moorland Restoration: potential and progress. In drivers of environmental change in the uplands. (eds Bonn, A., Allott, T., Hubacek, K. and Stewart, J.), pp. 432-447.
Phase 2	
Gully Blocking	Evans *et al* (2005) Understanding Gully Blocking in Deep Peat. Moors for the Future Report No. 4 www.moorsforthefuture.org.uk. Natural England and Moors for the Future (In Prep.) Moorland Restoration Handbook
Removal of Scrub and Woodland	Brooks and Stoneman (1997) Conserving Bogs. The Management Handbook. McAllister (2009) Water Management: Drain Blocking Techniques Review. Forest Research. Anderson (2010) Restoring afforested peat bogs: results of current research.
Re-introduction of *Sphagnum*	Carroll *et al* (2009) Moors for the Future Report No 16 *Sphagnum* in the Peak District Current Status and Potential for Restoration. www.moorsforthefuture.org.uk Hinde *et al* (2011) Moors for the Future Report No 18 *Sphagnum* re-introduction project: A report on research into the re-introduction of *Sphagnum* mosses to degraded moorland Quinty and Rochefort (2003) Moorland Restoration Guide. Natural England and Moors for the Future (In Prep.) Moorland Restoration Handbook.
Sustainable Grazing	Natural England and Moors for the Future (In Prep.) Moorland Restoration Handbook Backshall *et al* (2001) The Upland Management Handbook. Scottish Natural Heritage (2008) Scottish Wild Deer Best Practice Guidance.

Moors for the Future, amongst others, have had some success in developing ‘best practice’ methodologies for peatland restoration. The establishment of best practice methodologies has not been helped by the lack of uniformity in the starting or end point of restoration (Weinstein *et al* 2001) The causes of peatland degradation are often multiple. Identifying and prioritising restoration for the most limiting factor is vital. This can be different for each site and often even with best practice methodologies there is no substitute for experience. Successful restoration can only be achieved through a combination of securing sympathetic land management; sufficient resources and the application of appropriate restoration techniques and skills.

5. Evidence for the Success of Peatland Restoration

The following subsections (5.1- 5.3) provide a summary from the research literature on what we know and do not know about the successes of existing peatland restoration practices. The majority of the discussion relates to the summary of findings presented in Table 5.1.

***Table 2** Assessment of the literature summarising current understanding of the effects of peatland restoration techniques on ecosystem services*

	Restoration	**Stability and Height of Water Table**			**Peat Stabilisation / Carbon Sequestration**			**Biodiversity** (Common Standards Monitoring Assessment Targets[1])		
		1 Year	1-5 years	5-20 years	1 Year	1-5 years	5-20 years	1 Year	1-5 years	5-20 years
Water Management	Ditch blocking and gully blocking	↑[2]	→[2]	↑ with mire vegetation recovery	→[3]	↑ with terrestrialisation	↑ with paludification	→[4]	↑[5] with mire vegetation recovery	→
Restoration of Bare Peat	Seed with lime, fertiliser grasses and heather	↑[6]	↑[7]	→	↑[8] reduced erosion	↑[9]	↓ continued oxidation at a reduced level	↑[10]	↑[11]	↑
	Stabilisation with geo-jute and heather brash	↑[13]	↑[14]	→	↑[15] reduced erosion	↑[16]	↓ continued oxidation	↑[17]	↑[18]	↑
Vegetation Management	Introduction of *Sphagnum*	→[20]	↑	↑	↑[21]	↑	↑	↑[22]	↑	↑
	Molinia and heather reversion	↑[35]	↑	→	↑[35]	↑	→	↑[35]	↑	→
	Removal of grazing	→[23]	→	→	→[24]	↑ reduced trampling	→	→[25]	↓[30] depends on starting point	→
	Cessation of burning	→[26]	→	↑ with mire vegetation recovery	→[27]	↑[28] return of *Sphagna*	↑ with further recovery of mire vegetation	↑[29]	↑[29]	↑ but decrease in some bird species
	Removal of scrub and woodland	↑[32] reduced water uptake	↑	→	↓[33] reduced Co_2 uptake	↑ with *Sphagna*	↑	↑[34]	↑	↑

Key: ↑ Increase, ↓ Decrease, → No change. Note that as presented the arrows are relative to the previous period, so that increase in year 1 followed by stable conditions in the next five years is indicated as a sideways arrow in year 1-5
No colour = Empirical Evidence
Blue = Logically expected from current knowledge but no clear empirical evidence
Red = No data, effect unknown

Supporting literature [1]JNCC (2009), [2]O'Brien *et al* (2007) [2]Armstrong *et al* (2009), [2,3]Holden *et al* (2009), [2,3]Worrall *et al* (2007c) [3]Wallage *et al* (2006), [3]Holden *et al* (2007), [4]Carroll *et al* (2009), [4,5]Tallis (1998), [4,5]McMorrow *et al* (2009), [6,7,13,14]Allott *et al* (2009), [8,9,15,16] Evans *et al* (2009), [9,14,16]SCaMP 2010), [20]Holden *et al* (2008b), [8,15]Worrall *et al* (2009b), [10,11,17,18]Anderson *et al* (1997), [4,5, 10, 11,17,18,22,35]Anderson *et al* (2009), [23,26]Worrall *et al* (2007a) [23,26]Clay *et al* (2009b), [24]Van der Wal *et al* (2003) [25,29]Williams (2006) [27,28]Kuhry (1994), [27,28]Garnett *et al* (2000), [27,28]Ward *et al* (2007), [27,28]Clay *et al* (2009a) [27,28]Worrall *et al* (2010a), [28]Rawes and Hobbs (1979), [28]Rodwell (1991) [28]Ratcliffe (2002), [29]Hobbs and Gimingham (1984), [29]Tucker (2003), [29]Ramchunder *et al* (2009), [30]Pearce-Higgins *et al* (2009), [32] Price *et al* (2003), [34]Anderson (2010), [34]McAllister (2009), [34]Anderson *et al* (2000) [35]Anderson *et al* (1997)

5.1 Water management

Water management refers to peatland restoration practices involving the blocking of drains and erosion gullies; for valley mires and fens this could also include irrigation or flooding measures. In terms of the restoration of the three components of a peatland (water, peat and vegetation) , rewetting or returning water to relatively stable near surface (5-10cm) levels is the least controversial and most successful (Holden 2009; Armstrong *et al* 2009; UU SCaMP 2010) However there are still a number of uncertainties over how long and, in some situations, if it is possible, to restore the hydrological function of the acrotelm peat layer (Holden *et al* 2004; Carroll *et al* 2009; Lindsay 2010)

Whilst carrying out this review it became apparent how little published research there is on vegetation response to hydrological restoration. Much of the available data are unpublished and with intact vegetation typically taking 2-5 years to show any significant recovery it may be some time before we can provide a full assessment of the effectiveness of recently established hydrological restoration methods to restore mire vegetation. Vegetation changes in response to hydrological changes are also heavily dependent on burning and grazing management regimes. It is likely that on dry peatlands, dominated by *Calluna,* change to vegetation will not occur or only occur very slowly unless burning management is removed (which favours *Calluna*) In these heather monocultures it is also likely that the re-introduction of peat forming plant material will be required. The presence and impact of soil piping may also affect the success of hydrological restoration measures (Holden 2009)

Table 5.1 shows that the water table in the peat can recover within 1 year following the blocking of drainage ditches (Holden 2009; Wallage *et al* 2006, UU SCaMP 2010a) This recovery is usually very local to the drainage ditch. However ditch blocking has been shown to prevent interception of surface flow by drains thereby increasing contributing areas and allowing downslope rewetting with increased water storage and more stable water tables (Holden 2009, Wilson *et al* 2010) The blocking of gullies is effective in narrow v shaped headwater gullies for raising adjacent water tables (O'Brien *et al* 2007) but inherently less successful than ditch blocking in removing drainage lines as gullies form part of the dendritic drainage system.

A variety of materials have been successfully used to block gullies and ditches. The materials can be grouped into those which are semi-permeable and those which are impermeable. Semi-permeable materials such as moorland bales, peat, stone and wood have proved particularly successful at trapping sediment in gully systems (Evans *et al* 2005) Plastic shuttering or peat dams which are impermeable if densely packed are more commonly used to block drainage ditches and gullies (Holden 2009) Impermeable dams on average result in higher water tables but have the disadvantage that less sediment is trapped by the dam, attributed to higher scouring energy (Evans *et al* 2005) The choice of material used in dams is often determined by local availability and success is more often determined by the circumstance. Sand filled hessian sacks and semi-permeable dams are more likely to succeed in gully systems where energies are higher and the intention is not to prevent the flow but to slow it and allow consolidation of peat/sediment and re-vegetation.

There is evidence that ditch blocking and, to a lesser extent, gully blocking reduces losses of particulate organic carbon in runoff from peatbodies in the first year following blocking provided any bare peat in the catchment has also been treated (Freeman *et al* 2001; Worrall *et al* 2007b,c; O'Brien *et al* 2007, 2008c; Evans *et al* 2009; Holden 2009; UU SCaMP 2010) This reduction in sediment run-off has positive impacts on raw drinking water quality and reduces sedimentation in catchment reservoirs. Changes in water colour associated with dissolved organic carbon (DOC) in the first few years after blocking are more variable and site specific, although a UK wide survey showed a general pattern of reduced DOC loss and water discolouration (Armstrong *et a*l 2010) In situations where a relatively dry bog has been rewetted using blocks, the levels of DOC in run-off and peatbody water can increase immediately after dam installation (UU SCaMP 2010) This has been described by Lindsay (2010) and appears in part to be due to revitalisation of the microbial community and flushing of mineralisation products (Figure 4) This appears to be a short-term effect and where monitoring data exists for 3 or more years DOC levels generally show reductions (Wallage *et al* 2006; UU SCaMP 2010; Armstrong *et al* 2010)

There has been a great deal of anticipation that peatland restoration measures, and particularly grip blocking, would help with flood water attenuation and flood risk alleviation in sensitive catchments. Comparisons of hydrographs pre and post restoration suggest initial reductions in peak flows in response to blocking (Holden 2009, UU SCaMP 2010) Grayson *et al* (2010) have also shown changes in storm hydrographs in response to long-term peatland vegetation change, with peakier hydrographs and higher mean peak storm discharge associated with periods with greater bare peat cover. A common perception is that restoration will affect stormflows via water storage effects within the peat, but as restoration results in increased water tables the consensus amongst our review teams is that in a degraded peat body, additional hydrological storage is typically small and in large storms will be a small proportion of the total runoff (Evans *et al* 1999; Holden and Burt 2003; O'Brien *et al* 2007) It is more likely that flow attenuation is controlled by changing surface flow conditions and/or surface storage effects. Holden *et al* (2008b) demonstrate that overland flow velocities are associated with surface cover type, with highest velocities on bare peat and slowest on areas of S*phagnum* cover. Holden (2009) also considers the potential role of grip blocking in 'slowing the flow' of water across peatlands by the diversion of water from drains onto the peat surface. There is therefore some empirical evidence to suggest that ditch blocking, re-vegetation, and the introduction of S*phagnum* would have benefits for stormflow attenuation. However, these data are limited and further studies are needed to confirm both the key processes controlling stormflow response in restored peatlands and to demonstrate the scale of the effects.

Table 5.1 shows our assumption that, in the short to medium term following rewetting, rates of carbon sequestration are likely to increase, particularly in situations where the peatland plant community remains relatively intact (Worrall *et al* 2007d; Worrall *et al* 2009) Recent studies have also shown short to medium term increases in methane generation following rewetting

(Baird *et al* 2009) However Lindsay (2010) suggests that the emissions levels measured do not exceed the range observed from a 'pristine' peatland system. Lindsay (2010) also states that emissions may be temporarily increased, particularly following rewetting of drained bogs, and that any calculations of GHG emissions need to take account of 'avoided losses' due to the continued release of CO_2 in drained bogs due to peat wastage. It is of vital importance that we recognise that until a functioning acrotelm layer has been restored, peatbodies will continue to lose carbon whether in the fully oxidised gaseous CO_2 or as methane. Release of methane has been shown to be most significant from open peat bog pools following rewetting. Where there is intact vegetation or where a floating raft of *Sphagnum* is present, emissions of methane are much reduced (Raghoebarsing *et al* 2005; Worrall *et al* 2007b, d; Baird *et al* 2009; Lindsay 2010) Raghoebarsing *et al* (2005) found that the majority of methane formed in intact peatlands is consumed by methanotrophic bacteria which form a partly endophytic symbiosis with *Sphagnum* mosses, leading to highly effective in situ methane recycling in peatlands with a covering of *Sphagnum*.

Significant gains have been made to lowland fens and mires where it has been possible to isolate the peat body from the often negative influences of surrounding intensive agriculture. Environmental stewardship schemes when targeted to immediate catchment areas have been very successful (Labadz and Butcher 2004) Acquisition of the peat body or surrounding land areas by private and government nature conservation organisations has also proved very effective (English Nature 2002) Evidence is required to determine if the acquisition of damaged lowland peat bog for carbon off-setting is a cost effective option for the future.

In lowland raised bogs the most frequent used best practice technique involves the raising of the water table to within 10 cm of the soil surface to maintain saturation throughout the year (Brooks and Stoneman 1997, Labadz *et al* 2002) Frequently, the regeneration of *Sphagnum* vegetation is only observed in the shallow and sheltered margins of the flooded areas, where *Sphagnum* growth leads to the formation of loose floating rafts (Meade, 1992) For the formation of *Sphagnum*-dominated vegetation in deeper water (>50cm) a raft of floating peat is critical to restoration success. However the growth of most aquatic *Sphagnum* species seems to be strongly limited by the availability of dissolved carbon and light (Wheeler and Shaw 1995; Smolders *et al* 2002)

Buoyant peats form ideal sites for the colonisation of *Sphagnum cuspidatum* and *S. fallax (*Smolders *et al* 2002; Lamers *et al* 1999*)* Methane bubbles trapped in the peat help to maintain buoyancy. In the majority of cut-over sites the peats have become very acidic and compacted which is unfavourable for the microbes which produce methane (Lamers *et al* 1999) Where inundation does not form peat rafts *Sphagnum* colonisation will only occur in sheltered areas and shallow margins and only then where the water levels remain at or within 10cm of the peat surface. The level of inundation is critical, as is the nutrient status of incoming waters (Smolders *et al* 2002)

One of the most recent techniques to be used extensively for restoring lowland raised bogs following the removal of trees, is to use the peat to construct shallow bunds after the ditches have been blocked. There is little published information on the success of this relatively new technique. Natural England (pers. comm.) report mixed results depending on the extent and depth of inundation. *Sphagnum* colonisation, particular *S. cuspidatum, h*as been extensive in 3 years in situations where cell size is small (typically 20x20m) and water depth less than 10cm. Where large areas of standing deep water are created surface waters are subject to wind disturbance and typically colonised by ducks, geese and gulls, bringing with them significant nutrient inputs, reducing *Sphagnum* colonisation.

Please consult IUCN review Topic 6 for further information on the 'peatland hydrology'.

5.2 Revegetation of bare peat

As indicated in Table 5.1, a great deal of success has been achieved by stabilising bare and and highly eroding areas of blanket peat with a heather dominated and nurse grass seed mix (Figure 5) Successful techniques for stabilising areas of bare peat have been reported for the Peak District and the Southern Pennines (Anderson *et al* 1997; Buckler *et al* 2007; Carroll *et al* 2009) In the Pennine situations the acidity of bare surface peats (typically <pH 3.5) prevents the re-growth of vegetation. In these situations the first phase in the restoration to an 'active' blanket bog involves the addition of granulated lime and NPK fertiliser in association with heather and nurse grass seed species. Granular lime is added to increase the pH at the peat surface to 3.8 (Anderson *et al* 1997), sufficient to allow vegetation establishment. This method has proved very successful, with re-vegetation and peat stabilisation commonly occurring in 3-5 years (Anderson *et al* 1997) The addition of lime and fertiliser should only be carried out on bare eroding peat following analysis of the peat chemistry and in conditions where re-vegetation would not otherwise be possible.

Improvements have also been shown in water quality with immediate reductions in POC losses following the implementation of standard methods of re-seeding (Section 4.2) on bare peat areas (Evans *et al* 2009, UU SCaMP 2010) In contrast vegetation establishment on these severely degraded sites produced no immediate reductions in DOC (UU SCaMP 2010) Concerns have been expressed during the consultation exercise over the lack of information on the potential effects of lime and fertiliser addition on the subsequent recovery of bare peat to an 'active' peat forming vegetation. Research by Caporn *et al* (2007) suggests that the effects of lime and fertiliser are short-lived but there remains a requirement for further research particularly in relation to potential changes in the microbial community.

Following the establishment of a nurse grass and heather seed mix on bare peat Anderson *et al* (1997) suggests that it can take about 10 years for a facsimile of 'active' blanket bog vegetation to replace the introduced vegetation. Further research is required following the use of nurse seed treatments to determine if there are circumstances where the nurse seed mix establishes itself as dominant. Where heather cover becomes dominant and wildfires become more prevalent, it is likely that this would prevent the colonisation of *Sphagnum*. and the long term goal of restoration to 'active' peatland. If, following peat stabilisation, the plant species composition moves to a more natural state with bryophytes and dwarf shrubs, then initial dominance of heather may be a small price to pay given the highly degraded starting point of the bare peat. Re-vegetation of bare peat has also been shown to reduce runoff velocities (Holden *et al* 2008b) This is potentially the largest impact of restoration on flood runoff/timing.

Re-vegetation of eroding peat surfaces on slopes at the edge of peat bog and where peat haggs occur are particularly problematic and require stabilisation prior to vegetation establishment. This is most commonly achieved by anchoring biodegradable geotextiles to the peat surface. Geojute has been shown to reduce frost heave effects and, when in combination with lime, fertiliser, grass seed nurse crop and *Calluna* seed, allow establishment of vegetation (Anderson *et al* 1997) Although effective, the use of geotextiles is expensive and generally targeted where problems are severe and no natural alternatives are available.

Where areas of peat erosion are less extensive or severe, a more natural and cost effective method of peat stabilisation and re-vegetation involves the spreading of heather brash cuttings, with the seed still intact on the plants, harvested from adjacent areas. Establishment of a heather dominated sward usually takes 2-3 years and will make no contribution to carbon sequestration and only a limited contribution to biodiversity targets (JNCC 2009) Results suggest that it may prove to be a good first step in the restoration process and a secure holding position for severely degraded peatbodies. Other species such as *Empetrum nigrum, Eriophorum angustifolium, E. vaginatum* and *Erica tetralix*, have also been added as plants grown from cuttings or plug plants, with good successes in restoring a typical moorland vegetation of cotton-grasses and ericaceous shrubs (Anderson *et al* 1997)

Restored vegetation does not necessarily revert to the pre-damaged state and new vegetation can move in different directions. On shallow peats (and/or mixed with clays and silts) with a constant flow of ground water, rushes can invade and prevent other species colonizing (Marrs *et al* 2004) However they do not persist on peatlands that have a high, stable, water table.

Figure 5 *Initial results of a nurse grass and heather seed restoration mix on bare and eroding peat seeded in spring on Ashway Gap, Peak District (SCaMP project) (Source Penny Anderson Associates)*

5.3 Vegetation management

This section provides a summary of research findings following changes in land management practices. Much of the damage to peatlands is the result of cumulative impacts that often include land management practices, which cause loss of *Sphagna* and active peat forming processes, such as burning, over grazing and afforestation. There is a great deal of debate in the literature regarding the impacts of burning and grazing on bog vegetation. Much of this confusion results from associated research in to the impacts of these practices in managing dry heather moorland. *Calluna* dominated dry heath on shallow peat or mineral soils where bog building *Sphagna* makes only a minor contribution to the total biomass is not normally actively peat forming. In this vegetation we would expect these land management practices to be less damaging. In contrast burning management on deep peat leads to the dominance of *Calluna* allows higher DOC levels to be generated and less or no carbon sequestration as the peat is drier (after destruction of the original bog vegetation through burning) Nature conservation restoration objectives in this situation are to reduce the dominance of *Calluna* and restore bog vegetation. This objective is often seen to conflict with that of Grouse moor owners.

Restoration measures involving changes in land management, although less intensive, have the advantage that they have a low capital cost compared to the restoration of bare peat and can take place over large areas. In terms of gains to biodiversity and carbon sequestration, less intensive and more extensive, in terms of area, changes can lead to greater gains. The most extensive impacts in degraded peatlands are associated with loss of cover of *Sphagna*. In the majority of cases no one limiting factor such as drainage is responsible for this reduction in *Sphagnum* cover. The secret to the success of any restoration scheme is to identify all limiting factors before you begin work. Established plant species assemblages respond slowly to land management changes. There is an inertia as a result of the physical presence of the existing sward and because plant species are generally preselected to influence the environment for subsequent generations. What is often needed is a “kick” to deflect these often stable species assemblages into positive change. In the absence of a major deflecting force, species change in response to the implementation of favourable management is likely to be slow.

5.3.1 Introduction of *Sphagnum*

Successful restoration of a moorland vascular plant assemblage should only be considered as Phase 1 in the restoration process. Restoring a *Sphagnum* dominated surface layer is vital to restoring an acrotelm layer with fully functioning hydrological properties and which can form an active carbon sink (Brooks and Stoneman 1997; Schumann and Joosten 2008; Lindsay 2010) Phase 2 is the restoration of the acrocarpous mosses, in particular the *Sphagnum*. Restoring the correct *Sphagnum* moss species is proving much more challenging and, at least in the UK, is very much a work in progress (Carroll *et al* 2009; O’Reilly 2008, http://www.moorsforthefuture.org.uk/node/144) This is exacerbated in some parts of the UK by the residual effects of SO_2 deposition on peat surface pH and continued atmospheric deposition of nitrogen (Yeloff *et al* 2006) Deposition rates as low as 10kg ha^{-1} yr^{-1} of nitrogen have been shown to have a significant negative effect on *Sphagnum* growth (Gunnarsson and Rydin 2000)

Successful restoration also requires the identification and removal of the limiting factors, most likely to be the absence of a permanently near surface, stable water table. In some situations the limiting factor for new species colonising would appear to be the absence of suitable plant propagules and/or colonisation gaps. There are many examples of the successful addition of *Sphagnum* as diaspores, most notably in Canada and the USA, where this method is used routinely to restore cut-over peat following commercial peat extraction (Quinty and Rochefort 2003) In the UK, such methods have been used less frequently and mainly restricted to raised bogs (Wheeler *et al* 1995; Money 1995) Success has been found particularly in the introduction of pool species such as *S. cuspidatum* and *S. fallax (*Carroll *et al* 2009*)* and in ditches where small amounts of these species occur, full cover is possible 2-3 years post blocking. The reproduction of *Sphagnum* lawn species has been more problematic: successes have been achieved where appropriate stable water levels have been combined with the introduction of a suitable structure or nurse species for establishment of *Sphagnum (*Carroll *et al* 2009*)*

Anderson *et al* (1997) used appropriate blanket bog nurse species in combination with geojute and a lime and NPK fertiliser mix, followed by a latter addition of liquidised dried pleurocarpous mosses (mostly *Hypnum*) Subsequent monitoring showed no difference between treated and untreated areas, which may have resulted from the negative impacts of fertiliser on the competitiveness of *Hypnum* in the introduced vegetation or the early stages of succession present that did not suit the moss. In raised mires *Sphagnum* growth is optimum for a pH range of 4-5 and weakly mineratrophic conditions. The consensus of opinion is that whilst lime and fertiliser addition allow optimum growth of nurse vegetation on bare peat, the boost in growth of the *Sphagna* provided by the fertiliser and lime may be outweighed under more optimal pH (>4) and nutrient availability by the competitive advantage provided to the vascular plants. The majority of lawn-forming *Sphagna* are highly efficient at scavenging cations from rainwater which enables them to persist in low nutrient environments, in a competitive refuge from the grasses and dwarf shrubs (Gunnarsson and Rydin 2000, Limpens and Berendse 2003)

5.3.2 Sustainable grazing

The main objective is to have grazing levels which do not cause loss of bryophytes and adversely affect the peat forming processes. The problem in the UK uplands is that the majority of our peatlands are already modified or damaged by past overgrazing and burning. Grazing management is seldom undertaken on land that is either not drained and/or burnt, therefore it is almost impossible to separate out the requirements for, or effects of grazing. There are several studies which have found, from monitoring long-term grazing animal exclosures, that 'light' grazing can have either a negligible or a slightly beneficial impact on bog vegetation (Rawes, 1983; Chapman and Rose 1991; Smith *et al* 2003) The explanation given for this observation is that grazers select out common and palatable grass species, reducing above ground competition for light. In sub-optimal conditions for mire vegetation it is likely that higher plants will shade out *Sphagnum* species or lead to loss through the accumulation of standing dead material in the absence of grazing. There has been much discussion in the literature regarding appropriate stocking levels for sustainable grazing (Worrall 2007a; Natural England In prep.) with limited data available for active peat forming communities.

Much of our existing degraded bog vegetation is grazing maintained. Grazing animals in general will seek out and preferentially feed on the more palatable species in acid grassland patches on the mineral slopes, moving to feed over bog and dwarf shrub heath vegetation when other resources are depleted (Natural England In prep) There are direct impacts of grazing such as sheep preferentially feeding on *E. angustifolium* runners, indirect impacts from the trampling damage (Bayfield 1979, Studlar 1980, Rawes 1983) and from potential nutrient enrichment. Vegetation passing through the gut is physically and chemically altered and more readily mineralised. Localised enrichment of nitrogen where animals have defecated is likely to preferentially favour the increased growth of higher plants over *Sphagnum* (Gunnarsson and Rydin 2000, Limpens and Berendse 2003)

The majority of restoration projects recommend the exclusion of grazing animals for the first 3-5 years (up to 10 where damage is severe) to reduce trampling and avoid the inevitable concentrated grazing where lime, fertiliser and nurse seed mixes have been applied (Carroll *et al* 2008) Lindsay (2010) comments that bare and degraded peatlands appear to be a particular features of countries which held high stock densities in their uplands. The vast majority of our upland vegetation is grazing maintained (Rawes 1983) Where carbon off-setting is the main objective for the restoration of blanket bog, it is likely that stock densities of 0.1sheep/ha all year (0.012LU/ha) or less on active blanket bog will be required for optimum rates of peat growth

(Natural England *in prep.*)There is still much research to be done to test whether ecologically sustainable levels of grazing can be compatible with economically sustainable levels of grazing.

5.3.3 Cessation of burning

Burning includes wildfires, the damaging effects of which all land managers seek to avoid. This section deals mainly with managed rotational burns, usually for a single species group (grouse) and whether it is compatible with the main objectives of peatland restoration.

It has long been established that the impacts of managed burns varied according to their frequency and intensity (Stevenson *et al* 1996) Burning has been shown to raise the substrate pH above 5 for a period of 3-5 years following the burn (Stevenson *et al* 1996) and degrade the micro- and macro-topography of the bog. There are also short-term increases in nutrient availability which are measurable for up to 5 years (Yallop *et al* 2006) Rawes and Hobbs (1979) reported that *Sphagnum* cover took between 0-7 years to recover to pre-burn levels. Certain *Sphagnum* species such as *S. compactum* appear to be more tolerant. Chapman and Rose (1991) suggest that light burns may be beneficial to removing litter. Lack of managed burning on dry moorland can result in a higher intensity of wildfire burns due to the build up of fuel (McMorrow *et al* 2009) However, wildfires are more common on heather and grass dominated degraded peatlands (Tallis 1998) and there is good reason to suggest that where the hydrological conditions of an active peat bog can be restored that susceptibility to wildfires will be reduced. Unfortunately there is a lack of empirical evidence for the impacts of managed burning on *Sphagnum* (Stewart *et al* 2005) However considering the ecological requirements of *Sphagnum* and microbiology of active peat bogs it is difficult to see how burning at whatever frequency on recovering or good condition peat bogs could be compatible with peatland restoration objectives such as carbon sequestration, biodiversity enhancement and improvement of water quality (Coulson 1992, Costigan *et al* 2005, Defra 2007)

Please see Worrall et al 2010c for further information on the impacts of burning on peatlands.

5.3.4 Removal of woodland scrub and trees

Restoration practices involving tree removal from plantation sites on blanket bog are extensive in Scotland, on lowland raised bogs and where drainage has resulted in natural encroachment of trees and shrubs. Tree growth on peat surfaces results in increased rates of evaporation and fall in water levels. This causes a drying and humification of the peat surface (Anderson *et al* 2000)

Removal of conifer plantations continues to be a priority particularly in parts of Wales, Northumbria, Cumbria and Scotland where extensive areas of forest plantation on deep peat have being felled, in some cases to waste, to restore peatlands (O'Brien *et al* 2007; Natural England 2010a) Restoration following tree removal has been possible where the hydrological dynamics have been returned to the pre-plantation state (McAllister 2009; Smith *et al* 1995) However in many situations humification and compaction of surface peat layers has resulted in changes in hydrological function, increasing the risk of invasion from undesirable plant species post clearance (Rydin and Jeglum 2008; O'Brien *et al* 2007; Anderson 2010)

Forest plantations are normally drained prior to plantation with fertiliser and lime added to aid early establishment of trees. Remnants of moorland vegetation often survive in the drains, along boundaries and rides and in areas too wet for tree growth. These foci provide excellent centres from which *Sphagnum* can spread following the removal of trees (McAllister 2009) Following rewetting the topography of the clear felled site with ridge and furrows is, along with the water chemistry (on coniferous sites), appropriate for the spread of *Sphagnum* (Lunt and Moon 2000)

Where rewetting is successful, significant *Sphagnum* growth over woody debris and in blocked ditches can be observed within two years (McAllister 2009, Anderson 2010; Lunt and Moon 2000) Problems can occur where birch tree seedlings establish following clear felling. On smaller lowland raised bogs hand pulling of seedlings, combined with the raising of water levels have been used to reduce tree re-growth (Lunt and Moon 2000)

5.4 Project text boxes

Box 1 The Peat Compendium: a compendium of UK peat restoration and management projects (2010)

The aim of the peat compendium is to provide:
- a website of peatland restoration and management activities across the UK;
- which is continually updated with new projects;
- allows dissemination of key project findings;
- and improves communication and knowledge transfer between practitioners.

The Peat Compendium contains details of over 170 UK peat restoration and management projects, split between lowland and upland Peatlands.

Fifty six of these projects were reviewed by Holden *et al* (2008a) Virtually all of the restoration sites have a nature conservation designation (SSSI PSA targets), with biodiversity identified as the main justification for restoration works. Hydrological function was the second most important justification factor. In recent years the emphasis has shifted to soil and water conservation, enhancement of carbon sequestration for climate change mitigation and flood protection goals.

The median budget per project was £241,000 (£1500 ha^{-1}), 55% of expenditure on practical works, with 20 years being the average estimate of time to achieving project aims. Over half of the projects occurred on privately owned land with multiple funding sources. Projects involving the restoration of blanket bog were three times greater in area than other types of peatland restoration combined.

The most commonly used restoration methods in descending order of number of projects were:
- rewetting (ditch and gully blocking);
- vegetation removal (scrub and conifers);
- control of grazing (largest area);
- reseeding and peat stabilisation (brash and geo-textiles);

The main challenges identified by practitioners were: physical access to sites; costs for purchase of equipment, health and safety considerations, opposition and a lack of expertise amongst contractors.

Almost all projects carry out some form of monitoring, vegetation (100% of projects) hydrology (70%), invertebrate and bird monitoring (50%), while carbon, peat erosion, climate and pollution are being monitored in few cases. Monitoring is mainly carried out through ground survey but assisted in about half of the cases by air photos and other remote sensing techniques.

Project staff reported significant improvements in hydrological condition and some improvement in carbon sequestering potential. However, there were no significant improvements in biodiversity or the proportion of peat that was intact. Improvements were typically reported within 3 years.

Holden, J., Walker, J., Evans, M.G., Worrall, F. and Bonn, A., 2008a. A compendium of peat restoration and, management projects.http://www.peatlands.org.uk/forum (accessed 19/7/10)

Box 2 United Utilities' Sustainable Catchment Management Programme (SCaMP) reports on the findings of large scale land management (2010)

This website below presents some of the results from the first four years (of an initial five year programme) of monitoring of United Utilities' Sustainable Catchment Management Programme (SCaMP) It focuses on the results of hydrological, water quality and vegetation monitoring on blanket bog on five estates in Bowland (Lancashire) and the Peak District (Derbyshire) associated with catchment-scale restoration works.

The key objectives of SCaMP were to meet the Government target of favourable condition for Sites of Scientific Interest (SSSI) by 2010 on UU's catchments, improve water quality, especially water colour but also sediment load and downstream flooding, ensure a sustainable future for the company's agricultural tenants and support UU's Biodiversity Strategy (supporting the UK Biodiversity Action Plan (BAP))

The measures to achieve these objectives that are the focus of this work included large-scale blocking of drains (grips) and revegetation of extensive bare peat (both on blanket bog), cessation of burning and the introduction of more sustainable grazing regimes.

Early findings of the SCaMP monitoring project strongly suggest that large scale land management changes in degraded blanket bog catchments can have significant environmental benefits in terms of ecosystem services. Initial results show:

- blanket bog SSSIs moving towards more favourable condition, through re-wetting of the peat and associated spread of *Sphagnum;*
- improved water quality in terms of its colour four years after grip blocking;
- reduced sediment load reaching streams two years after revegetation of bare, eroding peat;
- and increased peat groundwater levels and reduced peak stream flow following grip blocking which could have significant implications for downstream flood risk management .

http://www.unitedutilities.com/SCaMPdatalibrary.aspx (accessed 18/7/10)

6. Key Challenges for Peatland Restoration

6.1 Key uncertainties

There are many potential conflicts between restoration objectives. In particular, where the main aim of restoration is the return to active peat bog, several extensive land-use management practices such as forestry, peat cutting, drainage and managed burning are not compatible with preventing loss of or growth of peat. The evidence for the impacts of grazing and recreation on peat growth is inconclusive. Intuitively, all activities which have a direct impact on the cover of *Sphagnum* such as trampling (Bayfield 1979, Studlar 1980) or changes in the nutrient balance are likely to be damaging. Such conflicts also occur but to a lesser degree with nature conservation, with many peatland species and habitats reliant on some form of management (Pearce-Higgins *et al* 2009)

It is important to be clear about the objectives for restoration and appreciate where the main objective is carbon sequestration that this is likely to require compromise. Getting these objectives clear from the start of a restoration project can minimise conflict. It is possible with time (20-50 years cutover bogs) for all but the very modified peat bodies to recover to an active peat forming state once the degrading influence/(s) have been removed. However many restoration projects show no change or short term negative impacts on ecosystem services such as surface water quality and methane generation but where data exist, positive responses in the medium to long term.

There are three key stages in the restoration of an active peat bog: Firstly to restore the hydrology (water levels and quality); followed by the restoration of a stable peat surface or structure and finally; the restoration of a *Sphagnum* rich surface layer. Many studies have shown that vegetation can be slow to respond to restoration work in comparison to the hydrology (Jones *et al* 2004; Milligan *et al* 2004) To date in the UK we have been relatively successful in restoring the hydrology of drained peatlands and following forest planting. Methods for gully blocking are still in the development stage and it is too early to assess their overall effectiveness.

It is also important to recognise that restoration methods involving successful peat stabilisation result in significant reductions in carbon loss. Arguably preservation of existing stocks should be the first priority in peatland restoration. Stabilisation of eroding peatlands dramatically reduces carbon losses, particularly POC loss. The resulting short to medium term preservation of carbon stocks is important given the magnitude of the peatland carbon stock and buys time for more complete peatland restoration. The ideal situation would be to combine existing peat stabilisation methods with those required to restore carbon sequestration. This will require further development and testing of methods to restore *Sphagnum* cover.

Efforts are required to get the public, land owners and policy makers to recognize the value of peatlands for potential future carbon off-setting schemes in the UK. At present there is a lack of recognition and prioritization of restoration to *Sphagnum* rich, active peat-forming communities. Many local biodiversity action plans have a combined category “Upland or Moorland”, which combines blanket bog with dry and wet heath and fails to distinguish between active and degrading deep peat bodies (JNCC 2006; O’Reilly 2008)

There are many significant constraints which have been identified by local stakeholder groups. In many cases these are associated with a lack of priority given to peatland restoration such as the shortfall in funding, particularly non capital funding for staff, monitoring and land acquisition. Local opposition is also significant where restoration objectives are considered to conflict with present land-use and archaeological interests. Governance was also identified as a significant constraint (Holden *et al* 2008a) There is often an issue over the availability of suitably experienced and competent contractors to undertake restoration work and lack of technical guidance and training for contractors in restoration practice but also in risk assessment and project tendering (Matt Buckler *pers. comm.*)

An important point of agreement was that the most convincing argument for the funding of future restoration projects could be made using the multiple objectives of carbon sequestration, water management and biodiversity gain.

6.2 Monitoring of restoration targets

A major problem limiting what we know about the success of peatland restoration is the absence of much long-term monitoring data to inform future practice. The majority of restoration projects do not have baseline monitoring data: without these data we have no means of evaluating the success of restoration practices. Quasi-controls or reference sites have been used at a sub-catchment level to monitor change, but these data need to be interpreted with care and should not be used as a cheaper and quicker alternative for baseline monitoring. Where funds allow, pre-restoration monitoring of appropriate test parameters should be in place up to two years prior to restoration (O’Brien *et al* 2007; UU SCaMP 2010) Post restoration monitoring should occur for up to ten years (although not necessarily annually) to show short and medium term changes in surface water quality, discharge, vegetation recovery and peat processes (Bonnet *et al* 2009; UU SCaMP 2010) When evaluating the success of restoration, consideration should always be given to the future baseline i.e. the consequence of no intervention given the potential for future deterioration of peatland condition.

It is important that we draw a distinction between research and monitoring. Research provides the evidence on which we base future restoration practice. It requires scientific expertise, robust controls, often specialist analytical equipment and can be expensive. Monitoring is set-up to evaluate a predefined target, requiring the collection of pre and post restoration data using a standard survey method. Monitoring often requires the collection of data on key water parameters, vegetation and/or species of nature conservation interest. It need not be expensive and the type of data collected will depend on the objectives of the restoration. Assessment against predefined targets should be used to inform any changes in restoration practices on that site. A cost effective monitoring strategy could be to focus on vegetative recovery (in particular *Sphagnum* cover) and water table depth as proxies for restoration success. Many restoration projects lack criteria for judging success (Bonnett *et al* 2009) Monitoring needs to directly assess the objectives of the restoration work (Schumman and Joosten 2008) Ideally, it should focus on peatland function and be carried out over a sufficient time scale to show appreciable change.

The most important consideration in the restoration of degraded to active peat bog is the development of a new functional acrotelm, which, by its capacity for hydrological self-regulation, will be able to stabilise and maintain a near surface water level (Smolders *et al* 2002; Lindsay 2010) An essential requirement within this process of recovery to active bog is the growth of a *Sphagnum* rich surface layer. Where the principle objective is the restoration of a peat bog acrotelm layer for the sequestration of carbon then annual recording of the percentage cover of cotton grasses and *Sphagnum* species (*S. magellanicum, S. capillifolium* and *S. papillosum*), in the surface layer should be the main form of monitoring and a key attribute for judging restoration success.

The Joint Nature Conservancy Committee (JNCC) has produced a Common Standards Monitoring (CSM) condition assessment methodology which is used across the UK where nature conservation is the priority for restoration work (JNCC 2009) JNCC guidelines include the assessment of 5 key attributes which include vegetation composition, the extents of eroding and newly formed peat and disturbance from drainage, but unfortunately does not adequately cover the requirement for a significant % cover of *Sphagnum* (JNCC 2009) Where restoration to meet nature conservation objectives are the main concern, the monitoring of ground nesting bird populations can provide a useful indication of the condition of the peatland system, particularly in relation to the availability of invertebrate food sources (craneflies) However care needs to be taken as monitoring of any plant or animal group with the exception of the *Sphagna* and *Eriophorum* species cannot be used as a direct measure of active peat formation. Golden plover in the Peak District provide an excellent example of this where their distribution and breeding success can be related directly to the degraded areas of blanket bog (Pearce-Higgins *et al* 2009)

Please consult IUCN review Topic 3 for further information on the ‘peatland biodiversity’.

Hydrological monitoring combined with the recording of *Sphagnum* cover can provided an accurate picture of the condition of the peat body since both are direct measures of peatland processes. Water quality parameters such as POC and DOC in the peat body and in run-off provide a good indication of the rate of erosion and activity of decomposition processes Freeman *et al* (2001) The relationship between rainfall, discharge and water quality are important but the presence of colour cannot be used on its own to suggest a degrading peat body. Peat bodies and in particular the growth of peat is dynamic with seasons and years where the net accumulation of peat is zero. Provided the *Sphagnum* cover and the acrotelm layer remain largely intact in the medium to long-term, the peat body will continue to function as a carbon sink.

6.3 Climatic change and potential implications for success of peatland restoration projects

A significant future challenge is to understand how various climate scenarios, such as increased temperatures, summer droughts and higher intensity rainfall events are likely to affect peatlands. A lowering of mean water tables and oxidation of peat is likely to result in increased growth and competition from vascular plants which, in marginal climatic zones for peat formation, could make restoration to active bog challenging. In damaged blanket bogs, warmer drier summers, as predicted by climate change models, will lead to a drying of peat surface layers and an increase in wildfire (Garnett *et al* 2000; Yallop *et al* 2006; Worrall *et al* 2009) Rates of decomposition are controlled by a complex interaction of the environmental variables with microbes (Rydin and Jeglum 1998) There is evidence to suggest that, at least below the 500m contour line, the southernmost blanket bog peatlands in the UK exist at the 'marginal climatic zones for peat formation' (Worrall *et al* 2007d; Worrall *et al* 2009) If this were the case, then this could make attempts to restore active bog very difficult if at all possible in some locations. In these situations a strong case can still be made for restoration measures which preserve the peat that remains in these areas.

There is much debate regarding the ability of southern blanket bogs to withstand climate-change predictions (Belyea and Malmer 2004; Robroek *et al* 2006, Bonn *et al* 2009; Worrall *et al* 2009) The more optimistic view is that intact active peat bogs with *Sphagnum*-rich surfaces have the capacity to maintain their water logged conditions (Lindsay, 2010) It is certainly true to say that active peat accumulating in raised and even blanket bogs are found in France and Spain in what appear to be less favorable climatic zones. There is clear evidence from the peat-archive that blanket bog, even on the southern moors, was growing healthily under warmer climatic optima than those predicted for 2050 (Bindler 2006) Results from the modeling of climatic envelopes for British blanket bogs by Clarke *et al* (2010) suggests that the present day distribution of blanket bog is within the tolerances of predicted climatic envelopes for 2050 (IPPC 2006); with the main peat forming species *S. papillosum* continuing to grow throughout its current range. Robroek *et al* (2006) found, when investigating the effects of temperature increase on *Sphagnum,* that although growth was maintained at higher temperatures, there are likely to be resulting changes to the *Sphagnum* species composition of the bog.

The impacts of predicted climate change scenarios, such as reduced summer rainfall, are likely to be less significant for groundwater-fed mire systems than rain-fed blanket bog. It is not presently known to what extent blanket bog can derive moisture through occult deposition or what moisture losses could result from an increased average wind speed. What is evident is that there have been good rates of recovery of *Sphagnum* across the moors in south west England during the wetter summers (Lunt 2007-2010 *pers. obs.*)

Please see Worrall et al 2010b for further information on peatlands and climate change.

6.4 Conclusions

It is apparent from this review that there is an extensive and often ad hoc collection of monitoring data within the UK that is not at present being analysed and utilised to inform best practice. Ideally we need a government funded and co-ordinated team of multidisciplinary researchers to work with practitioners to evaluate the success of peatland restoration projects. In a role not dissimilar to Moors for the Future, this team would be responsible for providing best practice guidance and advice to practitioner and policy makers on what works. It is recommended that a meta-analysis of this monitoring data is performed and this would enable greater scientific understanding of UK peat restoration processes. The most effective forms of monitoring include the use of geographical information systems (GIS) and remote sensing techniques which require specialist skills and can be expensive. The are several projects (Yorkshire Peat Partnership, Natural England, Moors for the Future and University of Manchester) involved in developing the use of spectral analysis techniques and infra-red aerial photography for mapping and monitoring of a number of variables. Where support is available, these techniques provide the potential for up-scaling of restoration findings to a landscape or catchment level, which is particularly vital for assessing carbon sequestration.

The work of this review has identified a number of peatland restoration techniques, the success of which are supported by convincing scientific evidence:

Certainties

- The success of grip blocking methods in rewetting peatlands;
- The improvement in water quality associated with grip blocking;
- The success of *Sphagnum* reintroduction on clear felled lowland peat bogs;
- The success of methods aimed at stabilising bare peat;
- The importance of having a phased restoration to an active peat forming mire vegetation;
- The importance of peatland restoration in avoiding continued carbon losses.

The review has also identified restoration measures where there is a lack of academic consensus and published findings:

Knowledge Gaps

- The time frame for vegetation recovery following hydrological restoration on blanket bog;
- The effectiveness of gully blocking;
- The outcome of restoration using lime, fertiliser and nurse species on the regrowth of *Sphagnum*;
- The importance of rewetting on the frequency and damage done by wildfire;
- The impacts of grazing animals on carbon sequestration rates on active peatlands;
- The level of grazing that an active peat forming vegetation requires/can sustain;
- We have little or no information on the impacts of restoration techniques on the microbiology of the peat, which may prove vital to predicting carbon sequestration rates.

At this present time the coverage of standard guidance and transfer of experience on techniques used in peatland restoration is patchy. In particular there is an absence of guidance on:

- Methods for the introduction of *Sphagnum* rich surface layers to modified UK blanket bog;

- Methods for the reversion of *Molinia* and/or heather dominated areas to an active peat forming community;
- Appropriate circumstances for restoration using lime, fertiliser and nurse species;
- Methods for monitoring peatland restoration projects, including approximate costings;
- Recommendations for use of GIS and remote sensing data for peat restoration projects;
- Finally there is a clear need to establish a networking organisation for peatland restoration project managers.

It is anticipation that guidance on many of these techniques will be provided in the forthcoming Moorland Restoration Handbook (Natural England, *in prep*.)

In terms of opportunities for future restoration. Over-grazed, forestry and heather-dominated blanket bog make up the largest areas of degraded peatlands in the UK. Where economic returns on present land-uses are low, such areas offer ideal opportunities for landscape scale restoration projects. Research is required to provide best practice guidance for the restoration of *Sphagnum* rich surface layers to over grazed sites, coniferous plantations (following the removal of trees) and fire damaged habitat. Great success has been achieved in establishing higher plant species such as dwarf shrubs, cotton grasses and grasses on deep peat. However, where the main object is to restore active peat bog it is clear that there is no alternative to the restoration of *Sphagnum* rich surface layers. If no action is taken to restore our degraded peatlands it is clear that they will continue to decay and be net sources of CO_2.

In summary, the review identifies a number of inconsistencies in restoration aims and highlights potential conflicts between the objectives of securing future carbon sequestration and other land management practices. It recognises the value of existing restoration measures to stabilise eroding peatlands thus preserving the carbon stock. Also the need for more targeted restoration measures to restore peat bogs to an active state by securing high percentage covers of *Sphagnum*. In order to achieve this, greater account should be taken of the need to restore active peat, which should be made a condition of future government funding initiatives. At present, main restoration objectives are unclear or *ad hoc* with limited integration of environmental goods. A number of knowledge gaps have been identified with regard to the success of restoration measures. There needs to be a co-ordinated team of scientists to carry out monitoring, evaluate results and produce practitioner guidance. Restoration measures should seek to integrate better the key objectives of nature conservation, carbon sequestration and water quality. Attractive financial incentives need to follow restoration projects where there are likely to be clear, integrated and sustainable environmental gains. Pre and post restoration monitoring should be made a condition of funding (see Section 6.2) with the option for projects with demonstrated achievements to secure long-term funding.

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