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Restoration of degraded blanket bog (NEER003)

1st Edition - May 2013

NATURAL ENGLAND

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Natural England Evidence Review NEER003

Restoration of degraded blanket bog

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Published on 30 May 2013

ISBN 978-1-78354-003-7

Citation

This report should be cited as:

SHEPHERD, M. J., LABADZ, J., CAPORN, S. J., CROWLE, A., GOODISON, R., REBANE, M. & WATERS, R. 2013. *Natural England review of upland evidence - Restoration of Degraded Blanket Bog*. Natural England Evidence Review, Number 003.

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Acknowledgements

With thanks to; Evelyn Jack, Brigid Newland, Richard Pollitt, Katherine Milnes, David Glaves, and David Martin for their assistance in producing this report.

Cover photograph

Executive summary

Management of the English uplands is complex and achieving good environmental outcomes, while taking into account the needs of owners, stakeholders and other interests is a balancing act. An uplands evidence review has been undertaken in which a number of candidate topics have been considered. These topics were identified through stakeholder input, reflection on areas of advice subject to challenge and looking at what could make a difference on the ground. The five priority topics identified have formed the review programme and will help further the understanding of available evidence to support uplands management.

This topic review focused on a series of questions which were evaluated against scientific evidence. The topic review has also helped identify areas for future research; in the next phase, beyond the review programme, additional relevant information will be considered, for example social and economic factors, current working practices and geographic scale. The evidential conclusions drawn from these additional areas will help inform our future advice and practical management of the uplands on the ground.

Context

The Uplands of England are influenced by multiple users, each exerting a different range of pressures which can result in conflicting priorities. Natural England has a specific role in helping deliver the Uplands Policy Review; in particular through our research and evidence-based advice, our delivery of agri-environment schemes, and our partnership work with the hill farming and moorland management sector and rural communities to deliver a wide range of public goods and environmental benefits. To ensure that the best evidence underpins these strategies, Natural England has undertaken a review programme to gather and assess evidence on a range of key topics affecting the uplands. This topic review presents the evidence relating to the restoration of degraded blanket bogs.

The topic review process

The topic review has been carried out using a robust methodology to assess the balance of evidence concerning specific questions relating to blanket bog restoration. A total of 105 studies have been analysed and summarised for this topic review. This topic review uses the term blanket bog to refer to the habitat which forms blanket peat, and areas supporting predominantly blanket peat are termed blanket peatlands. Since blanket bog habitat can be lost through degradation, the scope of this topic review covers all blanket peatlands. Some evidence has been drawn from research on raised bog peatlands, which represent a closely analogous situation.

The individual questions addressed by this topic review can be summarised as:

- What are the features of an undamaged blanket bog?
- What plants form blanket peat?
- What managements or influences cause degradation to bogs, and how?
- To what extent do restoration management interventions restore bog functions and features?
- Specifically, what are the impacts of grip blocking and is it always necessary?
- Are any blanket peatlands inherently unrestorable?

Summary of conclusions

The wider implications of both degradation and restoration of blanket peatlands are considered in the context of the impacts of damage and restoration.

The review found that undamaged blanket bogs have high water tables which fluctuate in a layer overlying a permanently waterlogged layer of peat. They accumulate peat and are a carbon (C) sink, but emit methane. They have rapid stream responses to rainfall, slowed by any areas of *Sphagnum*, and have low export of dissolved organic carbon (DOC), but also contain some peat pipes.

Peat is formed due to waterlogging, therefore peat-forming plants are those adapted to wet environments. Several studies show that English and Welsh blanket peat is made up mainly of *Sphagnum* and *Eriophorum* remains, along with some remains of dwarf shrubs, but these do not form peat on their own. In some areas and layers there is a large component of unidentifiable grasses/graminoids that may represent *Molinia* remains.

Studies from Scotland show that ploughing and planting trees lowers water tables and causes subsidence of the peat. The topic review found evidence that ploughing and planting trees changes the ground flora, but may reduce methane, and there may be short term gains in carbon capture. Peat cutting can affect bog vegetation and peat left bare dries out on its surface, but not lower down in the peat mass. Cutting drains through blanket peat lowers the water table and discourages *Sphagnum*, while encouraging plants that like drier environments, especially downslope of the drain.

Individual studies report different impacts of drainage on catchment flow characteristics, but widespread surveys show that drainage is associated with more peat pipes. These surveys show that drainage can also accelerate erosion, especially on steep ground, although a recent meta-analysis suggests it is likely to reduce methane emissions. Experimental studies suggest that atmospheric deposition of pollutants may be damaging *Sphagnum*, but there is much evidence of recent *Sphagnum* recovery from across the country.

Land management practice such as drainage, grazing or burning often causes changes in semi-natural vegetation, and is often focused on increasing palatable species or encouraging vegetation dominated by ling (*Calluna vulgaris*). The evidence indicates that areas with more *Calluna* have more peat pipes and more dissolved organic carbon (DOC). Laboratory study suggests this vegetation has higher methane (CH_4) and carbon dioxide (CO_2) emissions than areas with *Sphagnum* or *Eriophorum*. There is some evidence that gullying and hagging, resulting from the development of small stream channels, also lowers the water table in some bogs. Further surveys show that this is most associated with high flat areas of bog, while linear gullies can also form in peat located on steeper slopes. Some palaeoecological studies suggest that gullies may represent channels formed over 200 years ago, and surveys and case studies indicate that they mostly erode slowly. However, other case studies in bare peat areas show more rapid erosion of up to 6 centimetres (cm) loss each year, losing peat into watercourses and by wind erosion.

Studies in Scotland and Ireland show that felling trees can encourage blanket bog vegetation to recover, especially if the plantation is young, or where disposal of waste wood on site by chipping is practised. Many studies demonstrate that bare eroding peat can be re-vegetated and stabilised using nurse grasses or heather. The success rate of this re-vegetation is helped by applications of lime, fertiliser, and stabilising treatments such as geojute. The evidence suggests this will help prevent loss of particulate organic carbon (POC), but will not prevent ongoing loss of peat as dissolved organic carbon (DOC) or as carbon dioxide (CO_2). Much research from Canada and elsewhere proves that cut-over peatlands can be managed to restore *Sphagnum*, provided the right combinations of water table, chemistry, species, mulches and/or nurse species are used. The evidence suggests that establishment of *Sphagnum* in English blanket peats would seem possible, but has not yet been fully demonstrated. Several studies show that the dominance of *Molinia* can be reduced with intensive application of grazing, cutting and or herbicides. There is some evidence that gully blocking will trap eroding peat sediment which will become re-vegetated.

Most studies show that blocking grips raises water tables, increases abundance and diversity of invertebrates, and there is some evidence that it encourages wetland plants over relatively short timescales. However, studies also indicate that the catchment flow properties and DOC export of grip-blocked peatlands differ between studies, suggesting that they do not rapidly recover to resemble those of undamaged peatlands or that other factors such as topography or vegetation may be more influential. Meta-analysis shows that grip blocking will probably decrease CO_2 emissions but increase methane emissions. A laboratory study suggests that methane may be reduced through leaving grip pools open, not infilling or reprofiling grips and by encouraging *Sphagnum* vegetation, rather than *Calluna* or *Eriophorum*, across the rewetted moor. A survey indicated that not all grips need to be blocked: those on shallow slopes will re-vegetate naturally, and may infill (though may still have a drainage impact).

The topic review found no evidence that any of our blanket peatlands are unrestorable, although costs of restoration effort may not be repaid rapidly by improvements in function, and the timescales for full recovery to approximate undamaged function may be long.

Research recommendations

There are a number of key areas for further evidence gathering, either by conducting a wider review or completing additional research, which would help to inform how best to restore degraded blanket bogs. These topics include:

- natural 'creep' of peat masses;
- peat formation by *Molinia*;
- multivariate and community analysis of peat profiles;
- impacts of afforestation on blanket bog birds;
- longer term impact of forestry or deforestation on peatland carbon balance;
- impact of drainage on DOC export, and on CO_2 exchange;
- impacts of atmospheric pollutants on wider bog plant communities;
- impact on peatland function of *Molinia* or its control;
- hydrological impacts of transpiration by vascular plants in bogs;
- recovery of water tables following deforestation;
- management of humidity to encourage *Sphagnum* recovery on low water table areas;
- control of over dominance of bog vegetation by *Calluna* or *Eriophorum vaginatum*;
- hydrological impacts of gully blocking;
- impacts of grip blocking on CO_2 flux, and holistic and multivariate; and
- properly replicated whole-catchment studies of grip blocking.

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1 Introduction

Background to the review

1.1 In March 2011 Defra published the Government's review of uplands policy which sets out a range of actions the Government, led by Defra, will take in partnership with others in the public, private and voluntary sectors to help secure a sustainable future for the English uplands. The actions in the Uplands Policy Review sit under four main themes:

- Supporting England's hill farmers.
- Delivering public goods from upland environments (including biodiversity).
- Supporting sustainable upland communities.
- Driving and monitoring change.

1.2 Natural England has a specific role in helping deliver the Uplands Policy Review; in particular through our research and evidence based advice, our delivery of agri-environment schemes, and our partnership work with the hill farming and moorland management sector and rural communities to deliver a wide range of public goods and environmental benefits. Our role in the uplands is also shaped by our broader role in the delivery of the government's Natural Environment White Paper and Biodiversity 2020 aspirations that focus on the enhancement and protection of ecosystem services and the natural environment, including improving the condition of England's SSSIs. Biodiversity 2020 targets for SSSIs are to achieve 50% in favourable condition and 95% in favourable recovering condition by 2020.

1.3 For these reasons it is important that our advice and decisions are based on sound evidence, and that our evidence processes are transparent and robust.

The need for the review programme

1.4 The English Uplands are extensive and include a range of biotopes, species, and land management practices. It is widely recognised that they provide provisioning, regulatory, and cultural ecosystem services.

1.5 As such, the uplands present a number of environmental conservation and land management challenges. This is particularly the case in understanding the effects of land management operations on upland biodiversity.

1.6 The review programme seeks to draw together the best available evidence on the effects of land management activities on upland biodiversity and ecosystem services. In doing so it provides a basis for advice and decisions on future management of the uplands.

The nature of the evidence

1.7 Over several decades a body of evidence has accumulated exploring the effects of different types of land management interventions on a range of upland ecosystem services, habitats and species. There is a wide variety of study types, for example before-and-after, correlation, and case-control studies, which may have taken advantage of opportunities for natural experiments. Randomised control trials are rare. Although there are many methodological differences within this research, notably the lack of consistency between measurement methods and different measures of outcomes, overall the results provide a basis from which conclusions can be developed about the effects of intervention and research needs.

1.8 It is worth noting a number of significant challenges associated with undertaking a review of the evidence on upland management interventions. Firstly, the search strategy needs to be broad enough to capture studies from non-traditional sources including those not indexed in environmental databases and work that may be in the ‘grey’ literature (such as project reports or case studies). Furthermore, studies may present invalidated measures that can be difficult to equate to effects on biodiversity or ecosystem services. Finally, the wide range of study types, for example ‘post-only’ measurements or uncontrolled pre and post studies, decreasing the predictive capacity of the research.

Overall scope of the Upland Evidence Review Programme

1.9 The uplands are a broad area encompassing a variety of habitat, species and ecosystem services, and subject to a variety of land management interventions. The overall review programme of upland biodiversity and ecosystem evidence will focus on five issues where there is significant challenge:

- The impacts of tracks on the integrity and hydrological function of blanket peat.
- The Restoration of Degraded Blanket Bog.
- The affects of managed burning on upland peatland biodiversity, carbon and water.
- Upland Hay Meadows: What management regimes maintain the diversity of meadow flora and populations of breeding birds?
- Impact of Moorland Grazing and Stocking Rates.

1.10 This review presents the findings of the restoration of degraded blanket bog topic. Consideration of other relevant information, such as social and economic factors, is an important part of the process of developing our advice, but is not part of this topic review.

Review topic: Restoration of degraded blanket bog

1.11 The global distribution of peat-forming habitats can be misleading, showing large expanses of mire girdling the northern hemisphere. Stretched out on a flattened map projection, these areas seem vast, but in reality northern peatlands occupy a relatively narrow band, and comprise only 3% of the earth’s land area (Brooks and Stoneman, 1997). The vast majority of these areas are the boreal peatlands that stretch across Canada, Scandinavia and Siberia, where peat accumulation is driven by cold temperatures and support huge coniferous forests. The type of largely treeless blanket bog found in the UK has a limited global distribution, and, with its near-analogous lowland version, raised bog, is found only in the north-west fringe of Europe and parts of south-west Canada, where there is relatively high rainfall, low nutrient supply and little disturbance.

1.12 These landscapes are harsh places for wildlife, so there is a limited diversity of organisms, and a band of few, specialist, stress-tolerant species survive. These include a wide range of red, green and ochre bog mosses *Sphagnum*, red-tinged cotton grass, wind-tossed seas of purple moor-grass, and purple-brown heather as well as tiny bog plants such as the insectivorous sundews and butterworts, the bright red berries of cranberry, the unexpected orange cloudberries or the yellow spires of bog asphodel. Curlew, golden plover and dunlin breed in these areas, feeding on abundant cranefly larvae, while hen harriers and short-eared owls hunt birds and small mammals. Unusual insects too, such as the bog hoverfly, bog bush-cricket and mire pill-beetle are also found in bogs. However, many of these are species which are not widely found elsewhere, and therefore provide beta diversity – a term which describes diversity of habitats: a diversity of biodiversity itself.

1.13 Despite their globally restricted distribution, in the UK blanket bogs form our largest areas of semi-natural habitats. Their importance to landscape and recreation is underlined by their position at the core of many of our wildest landscapes, including many Areas of Outstanding Natural Beauty (AONB) and National Parks. The peat stored by blanket bogs contains a disproportionately high percentage of our soil carbon, despite their lower area compared to mineral soils. Although 90% or more of natural peat can be made up of water, the remaining blanket bog peat material is typically 50% carbon and the total carbon it stores depends on the depth of the peat and its density: a 2 metre deep peat deposit can store approximately a thousand tonnes of carbon per hectare, around ten times that stored in a typical mineral soil. Besides storing carbon, this peat mass also contains a record of environmental changes, captured in both pollen and macrofossils that reflect the development of human civilization over the last 10,000 years. The lack of decomposition, which has allowed the accumulation of the peat also prevents degradation of rare wooden, leather and other organic artefacts, and can even preserve whole organisms, including ancient people, for thousands of years. However, blanket bogs, and the peat they deposit, are reliant on the conditions of waterlogging and low nutrients that enable the bog mosses and other characteristic plants to and animals to survive. Mismanagement of peatlands has the potential to disrupt this rare and restricted habitat, degrade its landscape, release its stored carbon as greenhouse carbon dioxide, and lose irretrievable environmental information.

The issue

1.14 This topic review will present a definition of an undisturbed blanket bog, and consider its characteristics and functions. It will review the impacts of management and other environmental factors on some aspects of the function and ecology of blanket bog and examine the impacts and feasibility of restoration management.

1.15 Blanket bogs are habitats that are characterised by the formation of peat in areas where the water supply is predominantly from precipitation. They typically form in upland areas, although they are also recognised at lower altitudes in higher latitudes (Tallis, 1998). They may support exactly the same assemblage of species as lowland raised bogs, from which they are distinguished only by their location, altitude, extent and presence of fringing fen 'lagg' vegetation (Brooks & Stoneman, 1997). Because they form peat, the extent of former blanket bog habitat is indicated by the extent of blanket peat deposits. Blanket bogs have been subject to changes in their environmental conditions through land management, climatic changes, and incidental environmental impacts such as air pollution. There is concern that these interventions have led to changes in their ecology and function. If the changes are accompanied by a loss of function, they can be considered to represent degradation of the system. In this case restoration management may be justified to restore the ecology and function of these blanket peatlands. Evidence is therefore required to identify:

- The characteristics and functions of an undamaged bog.
- What management causes loss or compromise of these functions (degradation).
- Whether, and how, this loss of function can be reversed or halted through restoration management.

What is considered in this topic review?

1.16 The question considered by this topic review is dependent upon a number of definitions, which effectively set the scope of the topic review and inform the interpretation of its findings. This section explains the definitions to be used, and thereby sets the scope of the paper. A glossary is also provided to further clarify definitions used in this review (Section 7).

1.17 A definition of 'blanket bog' and of the 'blanket peat' it deposits should set the scope of the review. Defining 'degradation' is required to understand the problem that restoration is aiming to address. A definition of 'undamaged' (good condition) status is required to understand the desired endpoint of restoration and understanding the terms 'functioning and active' should inform our understanding of undamaged bog.

Blanket bog

1.18 Blanket bogs are defined in the interpretation of Annex 1 of the Habitats Directive (EC, 2007) as:

”Extensive bog communities or landscapes on flat or sloping ground with poor surface drainage, in oceanic climates with heavy rainfall, characteristic of western and northern Britain and Ireland. In spite of some lateral water flow, blanket bogs are mostly ombrotrophic. They often cover extensive areas with local topographic features supporting distinct communities”

1.19 This document lists typical species and National Vegetation Classification (NVC) types (M1; M15; M17; M18; M19; M20) and notes that raised bogs can, in some cases, coalesce to become blanket bogs, supporting the contention that these are ecologically analogous habitats.

1.20 Blanket bog is listed among the UK Biodiversity Action Plan (BAP) priority habitats (BRIG, 2010) and described in terms of its distribution and typical range of some characteristics. Important features in this description include:

- Inclusion of other mire types associated with true ombrogenous bog.
- Typical peat depth in excess of 0.5 m, but no agreed minimum qualifying peat depth.
- Typical vegetation of NVC class types M1, M2, M3, M15, M17, M18, M19, M20 and M25 and intermediates.
- Typically supporting a varying proportion of ling *Calluna vulgaris*, cross-leaved heath *Erica tetralix*, deer grass *Trichophorum cespitosum*, cotton grass *Eriophorum* species and several bog moss *Sphagnum* species, although not always.

1.21 The BAP restricts its scope to blanket bog meeting the criteria of supporting “semi-natural blanket bog vegetation, whether or not it may be defined as 'active'.” However, many of the areas where restoration of blanket bog is an aim fall outside this definition, such as those affected by coniferous plantations or those with predominantly bare peat. Thus to encompass the full range of restoration impacts, this review must not only consider blanket bog habitat, but areas where blanket bog habitat has previously existed.

Blanket peat

1.22 Because blanket bog is associated with ombrogenous peat, the distribution of blanket peat, regardless of its current vegetation, can be considered to be the extent of both degraded and undamaged blanket bog. It is possible that peat deposited by blanket bog vegetation currently no longer supports such vegetation, due to management or other factors. If this management can be considered to have delivered degradation of the original bog vegetation, these deposits of blanket peat should be considered as degraded blanket bog ecosystems and therefore fall within the scope of the topic review. Thus, the scope of this topic review includes all deposits of blanket peat, rather than the extent of current blanket bog habitat.

1.23 The extent of blanket peat in the country has been mapped at a large scale (NATMAP, 1:250,000 scale map of Soil Associations, NSRI), with broad areas of soil association defined by their composition of component soil series. Peat soil series are defined in Clayden and Hollis (1984) as soils comprising surface peat deposits either at least 40 cm deep; 30 cm deep over bedrock or litho skeletal material; or with less than 30 cm of pale mineral soil material overlying peat that extends at least 90 cm deep. Only the first two definitions are applicable to ombrogenous peat soils. Soil associations dominated by peat soils in the English uplands are WINTER HILL and CROWDY2. These soil associations may contain proportions of other peaty soils, shallower organic soils, and mineral soils, but are dominated by the WINTER HILL and CROWDY series, and form the bulk of the geographical scope of this review. Soil associations dominated by raised bog deposits include LONGMOSS, WESTHAY and TURBARY MOOR. The first of these is found in some upland fringe situations and is also included where it occurs in such situations.

1.24 For the purposes of this topic review, all areas mapped as WINTER HILL, CROWDY2 and upland areas of LONGMOSS are included. However, the definitions above allow blanket bog vegetation to occur on shallower peat. Therefore this topic review also includes any areas of blanket bog vegetation, approximating to the NVC communities listed above, regardless of peat depth. Areas falling outside these areas may be included if they support analogous (raised bog) vegetation, or provide information on the wider functioning of peatlands in other UK countries, or globally.

Undamaged blanket bog

1.25 Undamaged blanket bog, equating to blanket bog in good condition, is defined in this topic review by the set of target thresholds for a range of floristic and structural characteristics that are used in SSSI monitoring (JNCC, 2009). It is proposed that these thresholds are used as a benchmark to define undamaged blanket bog, and review the evidence of its properties and function.

1.26 JNCC (2009) define blanket bog in good condition as having:

- no loss of extent of blanket bog habitat;
- at least 6 indicator species present[1] in a 4 m^2 quadrant;
- 50% of the cover should consist of 3 indicator species;
- *Sphagnum* cover should not just be *S. Fallax;*
- *Eriophorum vaginatum*, ericaceous spp., or *Trichophorum cespitosum* should not exceed 75% cover individually;
- low cover of non-native species, trees and scrub (except dwarf species) and mesotrophic grasses/forbs/bracken;
- low grazing/browsing on dwarf shrubs, especially young ones;
- no burning into moss/lichen layers, or to expose the peat surface, and no burning on sensitive areas[2] assessed in the wider area;
- less actively eroding peat than re-deposited peat (in the wider area);
- less than 10% disturbed bare ground or showing signs of drainage or track damage; and
- less than 10% of *Sphagnum* should be damaged (crushed, disturbed).

1.27 Some of these thresholds relate to the extent of activities that are the subject of other topic reviews within this review programme. It would not be fair to use these as indicators of blanket bog in good condition for the purpose of this topic review, since for example, extensive drainage would automatically cause degradation by this definition. Instead this review will attempt to characterise undamaged blanket bog by the bold floristic characteristics only. If these characteristics are met, in vegetation approximating the NVC classes mentioned above, and/or on blanket peat deposits, then the site can be considered to be an example of undamaged peatland, and used to explore the functions and characteristics of this ecosystem.

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[1] *Andromeda polifolia*, *Arctostaphylos* spp., *Betula nana*, *Carex bigelowii*, *Calluna vulgaris*, *Cornus suecica*, *Drosera* spp., Erica spp., *Empetrum nigrum*, *Eriophorum angustifolium*, *Eriophorum vaginatum*, *Menyanthes trifoliata*, *Myrica* gale, *Narthecium ossifragum*, non-crustose lichens, pleurocarpous mosses, *Racomitrium lanuginosum*, *Rubus chamaemorus*, *Rhynchospora alba*, *Sphagnum* spp. (only *S. fallax* if in presence of >=1 other *Sphagum* spp.), *Trichophorum cespitosum*, *Vaccinium* spp.
[2] Broadly, these comprise steep slopes, carpets of *Sphagnum* or other lower plants, areas with rich microtopography, near pools, haggs, erosion gullies or near watercourses.

1.28 Most research papers do not characterise the conditions at the start of the study in sufficient detail to enable them to be compared to these characters. In many cases in this topic review it has been necessary to take the researchers' word that their 'intact', 'undisturbed', 'pristine' or otherwise undamaged peatlands approximate to the floristic description above. However, it is felt that the less disturbed comparators are more likely to reflect the conditions in undamaged peatlands, and are therefore included in this topic review as examples of these.

Functioning and active

1.29 Annex 1 (EC, 2007) and UK BAP (BRIG, 2010) define 'active', with regard to blanket bog, as meaning: 'still supporting a significant area of vegetation that is normally peat forming'. While this topic review accepts this definition of 'active' with relation to the question, it will seek to say 'peat-forming' to indicate where peat formation is actually occurring, and refer specifically to different species of plants, rather than assume that any of them are definitively associated with peat formation in that circumstance.

1.30 'Functioning' broadly means working: with ongoing or periodic processes occurring which deliver an outcome. It cannot mean complete stasis. Where such ecological functions are beneficial to society or to individuals, they are viewed as ecosystem services, while ongoing processes which deliver undesirable outcomes would be viewed as dysfunctional and therefore degraded. The beneficial outcomes of blanket peatland function broadly equate to the ecosystem services delivered:

- **Provisioning** - Producing products such as food (largely limited in blanket peatlands to grazing, game, honey, downstream impacts on fisheries), fibre (wool), fuel (peat/wood), timber, and water supply.
- **Regulating** - maintaining water quality, preventing damaging run-off, storing organic carbon (preventing potential climate impacts of its loss as CO_2), control of GHG fluxes, pollination.
- **Cultural** - blanket bogs may generate benefits that relate to societal cohesion, education, economics, aesthetics, academia, science, archaeology, recreation, health and well being.
- **Supporting** - These are ecosystem functions that are necessary for the production of all other ecosystem services, and could be seen to include nutrient cycling, soil formation, mediation of major global environmental cycles etc.

1.31 This topic review did not seek to compare the relative values of the beneficial functions, and indeed, some functions may benefit some sectors of society and disadvantage others. As such the topic review is restricted to analysis of the functions themselves. The topic review did not set out to include or exclude any specific ecosystem service, but the evidence provided by the studies predominantly related to regulating services, to a lesser extent, provisioning services (water yield and quality), and to biodiversity. Many of the key social, economic and cultural issues facing blanket peatlands are related to grazing and burning management and may be considered in other topic reviews in Upland Evidence Review programme.

Degradation

1.32 Degradation has been defined as a situation where the desired functions are not, or are inadequately, delivered. Thus factors that degrade blanket bog would include any management or environmental factor that causes a change in the function of the bog away from those that are desired. Blanket peatlands that fail to meet the CSM condition targets are those where the desired function of supporting blanket bog habitat is not being delivered. However, if the function desired is timber production, such bogs might be considered to be degraded land. This definition is subjective, since different functions are desired by different people, and different values placed on them.

1.33 As such it is proposed that, since condition targets define undamaged bog in floristic terms, the functions of a bog in this state are used as a benchmark for blanket peatland function for comparing the impacts of managements that affect blanket peatland function. Likewise, because restoration is only carried out on peatlands that are considered degraded, the comparison will be between those that have had their functions altered by management or other impacts, with those that have received restoration treatments.

The over-arching topic review question:

1.34 **What are the causes and impacts of degradation of blanket bogs and what interventions are required for degraded bogs to restore the functions and characteristics to those of undamaged bogs, and maintain these?**

The following sub-questions will be the focus of the topic review:

a) What are the hydrological, structural and floristic characteristics indicative of functioning and active blanket bog?
b) What species of plant are peat- forming and what are their physical (hydrological and other) requirements?
c) What factors (management, atmospheric deposition and climatic) affect the hydrological, structural and floristic status and composition of blanket bog, and leads to its degradation?
d) What interventions are required to restore a degraded blanket bog to a functioning and active blanket bog system with abundant peat-forming species, and over what timescale?
e) Does the blocking of artificial drainage channels (grips) on degraded blanket bog result in a functioning and active blanket bog with abundant peat forming species and representative bog flora and fauna. If so, do all drains need to be blocked?
f) Are there conditions where it is not feasible to completely restore a degraded blanket bog to a fully functioning bog system with its representative flora and fauna, and if so what is likely to prevent their full recovery?
g) Are there any wider environmental impacts resulting from the restoration of degraded blanket bogs?

Comparator

1.35 The comparators for the questions in this review are either:

1) blanket peatland biodiversity and other functions prior to intervention;
2) blanket peatland biodiversity and other functions where the intervention has not occurred;
3) blanket peatland biodiversity and other functions where different interventions have been applied; or
4) blanket peatland biodiversity and other functions where different environmental conditions have been experienced.

1.36 Interventions refer both to application of non-restoration management practices or occurrence of other environmental impacts and to application of restoration management.

2 Methods

2.1 This chapter briefly sets out how this topic review was undertaken following the approach described *Natural England Evidence Reviews: guidance on the development process and methods* (Stone, 2013).

Evidence search

2.2 Literature searches were conducted using the terms listed below. References were downloaded, or manually added if necessary, into a reference manager database (Endnote Web). References were also identified through web sites, and key reference lists. In addition, there was an open call to interested stakeholders to submit documented evidence for consideration as part of the review.

Search terms

2.3 The following search terms were used (an asterisk denotes a wild card search term allowing for several permutations of term):

Blanket bog, Blanket peat, Blanket mire, Peat*, Bog*, Mire*, Upland*, Moor*, Acrotelm, Catotelm, Bog pool*, Hummock*, Hollow*, Degrad*, Erod*, Erosion, Function*, Active, Inactive, Restor*, Recover*, Revegetat*, Regenerat*, Conserv*, Maintain*, Management, Rewet*, Remediation, Loss*, Bare, Change*, Hydrolog*, Structur*, Soil structure, Peat depth, Peat form*, Peat accretion, Peat development, Peat characteristic*, Peat composition, Water quality, Drain*, Block*, Grip*, Gull*, Carbon, Carbon loss, Carbon sequestration, Atmospheric deposition, Nitrogen deposition, Rain*, Temperature, Climate change, Graz*, Overgraz*, Burn*, Wildfire*, Mow*, Cut*, Herbicide*, Inoculat*, Nurse crop*, Brash, Bale*, Geojute, Flor*, Plant*, Vegetation, NVC, Sphagn*, Moss*, Eriophor*, *Calluna*, *Erica tetralix*, *Molinia caerulea*, Cotton grass.

2.4 The search terms of this topic review were based on habitats, vegetation types, plants and management interventions that were considered to be relevant to the topic. This has resulted in a primary focus of the topic review being on impacts on vegetation, hydrology and bio/geochemistry, and returned little information specifically aimed at impacts on fauna. However, faunal impacts were not deliberately excluded.

Search strategy

2.5 The following databases were searched:

Web of Science from 1990, CAB Abstracts from 1990, Zoological Records from 1978, Google Scholar, Scirus.

2.6 Publication searches were undertaken on:

British Library ETHoS, Countryside Council for Wales's library catalogue, COPAC, Collaboration for Environmental Evidence (CEE), Defra library catalogue (research repository), Natural England library catalogue, Peatnet, Peatscapes, SCaMP, water@leeds, Wiley Online.

2.7 Bibliographies and reference lists of the key review publications were also searched, for example, Labadz *et al,* 2010; Lindsay 2010; Littlewood *et al,* 2010; Lunt *et al,* 2010; O'Brien *et al,* 2007; Schumann and Joosten 2008.

2.8 The open call for evidence attracted submissions from 12 stakeholders. Of these stakeholders 10 were received from organisations, companies and groupings of individuals:

- Country Landowners Association;
- Environment Agency;
- Environmental Geology and Geotechnical Consultants Ltd;
- Federation of Yorkshire commoners and Graziers;
- Forestry Commission;
- Hebden Bridge Residents;
- Moors for the Future;
- National Sheep Association;
- Royal Society for the Protection of Birds; and
- Yorkshire Water.

2.9 In addition evidence was submitted by two individuals, by the External Reviewers for this report, suggested by the Appraisal Group and one paper was identified by the topic review author for inclusion.

2.10 The web sites for the major peatland restoration projects in England were also searched, for example, Moors for the Future, Yorkshire Peat Partnership and Peatscapes.

Selection of studies for inclusion

2.11 The search strategy resulted in 1258 titles. These were screened by title and abstract for relevance. In total 352 were identified as being likely to be relevant and the full papers were retrieved and evaluated. These are provided in Appendix 1. Of the 352 references, 159 were deemed relevant and selected for quality assessment and data extraction. These are listed in Appendix 2.

2.12 References on the impacts of tracks, burning and grazing on blanket bog were excluded as they were to be covered in other topics in the review programme (Glaves *et al,* 2013; Grace *et al*, 2013, Martin *et al,* 2013). References were excluded if the research was undertaken on plant species that were not found on English blanket bogs, or on hydrological conditions not typically found on English blanket bog.

2.13 Raised mires and other peatland types in the UK were included initially, as were peatlands in the rest of the world. A considerable amount of research on peatland restoration had been undertaken on raised mires in Canada and we did not want to lose that potential source of key and relevant data by applying exclusion criteria to raised mires and/or peatlands outside of the UK. This applied particularly to the blocking of ditches and the establishment of peatland species, notably *Sphagnum* mosses.

2.14 During the detailed analysis and quality appraisal of papers all duplicate studies were removed. Reviews representing a meta-analysis or a systematic review of results were retained. However, the majority of review studies were excluded because their source material could not be quality assessed. Several case reviews were included to provide general background on descriptive topics where information from intervention studies was not appropriate. One additional review was also included at the request of the assurance group to provide information in the area of moorland birds, where other references were lacking. All guidance documents, documents with low applicability (for example, southern hemisphere studies with few results) or documents without primary data were removed. This resulted in 93 studies remaining. A further 12 studies were identified and submitted by the external reviewers or report authors during the quality appraisal process, bringing the total number of studies in the review to 105.

Table 1 Numbers of studies identified in this review, and exclusion process

Review stage	Number of studies
Studies captured using search terms in all sources (excluding duplicates)	1258
Studies remaining after title and abstract filter	352
Studies remaining after full text filter	172
Studies remaining after reviews/guidance/low applicability/no results removed	93
With additional studies included following external reviewers' inputs	105

Study type and quality appraisal

2.15 For every study that was assessed, only the abstract or summary, methods and results section were considered in any detail. This was to ensure conclusions were drawn from the evidence presented in the studies as the primary source and avoided bias and conjecture. The details of the study were entered into a spreadsheet provided at Appendix 5, which records details of the study location, duration, interventions, measurements (type and frequency), statistical analysis, and results, as well as noting any specific issues relating to study quality or (lack of) interpretation. Each study was linked to Evidence statements which sought to address the key questions outlined in this review, and the analysis used to generate descriptions, and analysis, of each study which are provided in the Analysis of Evidence provided in this review.

2.16 Each study was categorised by study type (categorised as type 1-4) and graded for quality using a code '++', '+' or '-', based on the extent to which the potential sources of bias had been minimised. The studies were categorised into the following study types.

Table 2 Types of studies

Rating	Definition
1	Meta-analyses, systematic reviews of Randomised Controlled Trials (RCTs) or RCTs (including cluster RCTs). Also included randomised treatment/treatment trials where no control was appropriate.
2	Systematic reviews of, or individual, non-randomised controlled trials, case-control trials, cohort studies, controlled before-and-after (CBA) studies, interrupted time series (ITS) studies, correlation studies. Also includes other analytical studies (for example, comparative single site case studies).
3	Non-analytical studies, for example, case reports, case series studies.
4	Expert opinion, formal consensus.

2.17 Studies were quality appraised against quality criteria appropriate for study types, and subsequently classified into one of three categories (++, + or -).

Table 3 Quality categories of studies

Rating	Definition
++	All or most of the methodological criteria have been fulfilled. Where they have not been fulfilled the conclusions are thought very unlikely to alter (low risk of bias).
+	Some of the criteria have been fulfilled. Those criteria that have not been fulfilled or not adequately described are thought unlikely to alter the conclusions (risk of bias).
-	Few or no criteria have been fulfilled. The conclusions of the study are thought likely or very likely to alter (high risk of bias).

2.18 Synthesis of the 105 studies is presented in the Summary of findings (Section 3), analyses of all studies are presented in Appendix 5: Analysis of evidence and more details are available in Appendix 6: Evidence table.

Study categorisation

2.19 This section presents an analysis of the type, quality, and duration of the studies included in this review. Further details are given in Appendix 4: Study categorisation.

2.20 Of the 105 studies assessed, 27 were categorised as type 1 studies, 61 studies were categorised as type 2, 13 categorised as type 3 and the remaining 4 as type 4. Table 3 shows 17 studies were categorised as (-) quality, 46 studies categorised as (+) and 42 as (++). Table 4 shows the scoring for all individual studies assessed. The main reasons for studies being assessed as (-) quality were inconsistent or poorly presented results, lack of statistical testing, poor experimental design and failure to report sufficient environmental information.

Table 4 Study quality and type

Study type \ quality	++	+	-
1	18	8	1
2	24	26	11
3	0	8	5
4			

2.21 The largest category of primary research studies (31) included in this topic review were treatment/control comparisons, where impacts of one or more intervention, or combination of interventions, were compared with each other or with a control treatment of no intervention, or ongoing practice. A further 12 categories represented monitoring (repeated measures over time at locations where interventions had been put in place, but without obvious controls), 14 studies represented case studies (time limited, or one off descriptions of conditions at a small number of locations), 15 were surveys (widespread, one-off characterisation of environmental conditions), and 8 were before and after studies with no obvious control. The remaining primary research studies were controlled before and after studies, treatment/treatment comparison (where no control was available or appropriate), or combinations of several of these approaches (for example, control treatment comparison and survey). Four reviews were included where they provided descriptive information that provided background to the review that could not be derived from single studies or provided an overview of an underrepresented topic, along with one meta-analysis and one systematic review.

2.22 These studies tested a range of different environmental interventions related to the degradation and restoration of blanket bog and blanket peatlands. The studies relating to each of the sub-questions covered by this review are presented in Appendix 5: Analysis of evidence. The number of studies relevant to each question are summarised below:

- What are the features of an undamaged bog? (23 studies)
- What plants form blanket peat? (16 studies)
- What management or influences cause degradation to bogs, and how? (40 studies)
- To what extent do restoration management interventions restore bog functions and features? (41 studies)
- Specifically, what are the impacts of grip blocking and is it always necessary? (25 studies)

2.23 The majority (78) of studies were conducted in the UK, with a further 11 studies representing Canadian research, mainly into *Sphagnum* regeneration and conditions on cut-over raised bogs. Four or fewer studies represented research from Ireland, Switzerland, Sweden, Finland, Estonia, Czech Republic, Germany or collated data from worldwide review. More details of the location of studies are available in Appendix 4: Study categorization.

2.24 Most of the studies (66) considered measured outcomes of interventions over 12 months or more. A further 16 studies measured shorter term outcomes, and the remaining single intervention study measured outcomes over both long and short timescales. It was not possible or appropriate to assess the length of outcome measures in the remaining 23 studies. More information on the studies' duration of measurements is provided in Appendix 4: Study categorization

Assessing applicability

2.25 Each study was assessed on its external validity: that is, whether or not it was directly applicable to the target population(s) and setting(s) in the scope. This assessment took into account whether the study was conducted in the UK, any barriers identified by studies or the review team. On this basis only studies relevant to blanket peatland in the UK were included. If there were reasons to doubt whether the studies were applicable to any blanket peatland in the country, a note was made in the analysis of the evidence they presented.

2.26 However, to understand the external applicability of a study that compares or examines a peatland in one or more condition, one must have an overall picture of the general state of peatlands. This is beyond the scope of the review, but is provided by Natural England (2010) and by JNCC (2011).

Synthesis

2.27 This topic review is restricted to a narrative overview of all studies that met the inclusion criteria and contained sufficient data for data extraction and quality assessment. A full analysis capturing all intervention, measurements and results was conducted (provided in Appendix 6: Evidence table), while relevant specific findings are presented in the context of the individual restoration sub-questions in Appendix 5: Analysis of evidence. Both these outputs were used to generate and support the Evidence statements summarized in Section 3. These statements were generated to reflect:

- The best available evidence of the effect of an intervention.
- The strength (quality and quantity) of supporting evidence and its applicability to the populations and settings in question.
- The consistency and direction of the evidence base.

2.28 It was not appropriate to use meta-analysis to synthesise the outcome data as interventions, methods and outcomes were heterogeneous.

3 Restoration of degraded blanket bog - summary of findings

3.1 This section presents the Evidence statements that have been drawn from the studies reviewed in this project and links them to the evidence. Specific results drawn from analysis of individual studies are presented in Appendix 5: Analysis of evidence. A fuller analysis of these studies is presented in the spreadsheet appended to this report in Appendix 6: Evidence table.

3.2 The topic review then presents an overall synthesis, based on these statements, of the changing features and functions of blanket bogs as they become degraded from an initially intact starting point, and as they become restored from this degraded status.

Evidence statements

3.3 Provided below are the Evidence statements made by this review, arranged with relevance to the key questions. The strength of evidence is described in terms of strong, moderate, or weak. This is partly a subjective judgment, taking account of not only the number of supporting studies and their quality scores, based on the criteria in Table 3, but also a consideration of the aims and focus of a study. The strength of evidence is defined as follows:

- **Strong** - evidence from a number of studies, or one or two very high quality studies.
- **Moderate** - evidence from two or three studies, of which at least one must be a minimum of '2+'.
- **Weak** - one or a small number of low quality studies, usually includes ' – ' scores.

3.4 It has been judged on this basis that all the Evidence statements made in this section are based on strong evidence. Where the evidence of effects is not strong (ie moderate or weak), these have been identified as areas for further study, by more intensive review or additional research.

3.5 To ensure a consistent approach the key questions have remained unchanged during the whole review procedure. However, as mentioned in Section 1.11-1.36, the floristic characteristics of blanket bog in good condition have been used to define and characterise blanket bog in good condition, with reference to the NVC types and descriptions provided for European and UK policy instruments, and to the thresholds used in SSSI condition assessment monitoring. For this reason the floristic characteristics of functioning and active blanket bog have not been subject to review.

3.6 The impacts of different management and land uses on peatland carbon and greenhouse gas flux are considered throughout this review alongside other impacts. To enable systhesis of the topic, an overview of the evidence on this topic, across the range of intact, degraded and restored peatlands, is also provided in paragraph 3.32.

Key question: a) what are the hydrological, structural and floristic characteristics indicative of functioning and active blanket bog?

- Functioning and active blanket bogs are characterised by a high mean annual water table (5-10 cm from surface). (Holden *et al*, 2006 [2+]); (Holden *et al*, 2011 [2++]); (Wallage & Holden, 2011 [2+]); (Stewart and Lance, 1991 [2++]); (Burke, 1975 [3+]) and supported by (Murphy, 2008 [3-]); (Mackay & Tallis, 1996 [3-]). There are no studies that refute it.

- Active blanket bogs are characterised by a zone of fluctuating water table, with high hydraulic conductivity, overlying a thicker zone of peat with almost permanent waterlogging and low hydraulic conductivity (the catotelm). (Lindsay, 1995 [4]); (Lindsay *et al*, 2003 [4]); (Wallage & Holden, 2011 [2+]); (Holden *et al*, 2001 [2++]); (Holden *et al*, 2011 [2++]). There are no studies that refute it.
- Functioning and active peatlands accumulate peat, and peat carbon, through ongoing deposition of material into the catotelm. (Gunnarsson *et al*, 2008 [2++]); (Malmer *et al*, 1994 [3+]); (Chambers *et al*, 2007b [3+]) and supported by (Mackay & Tallis, 1996 [3-]). There are no studies that refute it.
- Peat pipes occur naturally in relatively intact peatlands. (Holden, 2006 [2++]); (Holden & Burt, 2002 [3+]); (Holden *et al*, 2012 [2++]). A further review study suggests that gullies are natural features of undamaged peatlands (Tallis, 1998 [4]). There are no studies that refute these statements.
- Functional and active blanket bogs generate predominantly surface and near-surface runoff and so are characterised by rapid flow responses compared to most other areas, but because the channel network is limited these do not necessarily give rise to such rapidly-responding (flashy) hydrographs compared to less intact peatlands. (Holden *et al*, 2008 [2++]); (Holden *et al*, 2006 [2+]); (Robinson, 1985 [2+]); (Robroek *et al*, 2010 [3+]).
- Runoff travels more slowly across *Sphagnum* dominated vegetation, than some other moorland vegetation types or bare peat. (Holden *et al*, 2008 [2++]). There are no studies that refute it.
- Intact (undrained) blanket peatlands export less DOC and water colour than drained or drain-blocked peatlands. (Gibson *et al*, 2009 [2+]); (Worrall *et al*, 2011 [2++]). There are no studies that refute it.
- Intact peatlands are net emitters of methane and emit more than drained peatlands and less than recently restored peatlands. A single study, representing data from 27 quality-assessed studies, supports this statement: (Bussell *et al*, 2010 [1++]). There was one study that could find no difference in methane flux between intact and damaged peatlands (Worrall *et al*, 2011 [2++]).

3.7 Some evidence suggests that gradual mass movement in peat may occur as a natural phenomenon (Shotbolt *et al*, 1998 [2++]), which may explain changes in peat surface elevation and topography, and interact with peat distribution and erosion on hill top peat. Peat 'creep' is mentioned briefly by Hobbs (1986) and this topic review (excluded from this study) may contain more pertinent information on the physical and engineering properties of peat (see Hobbs), that could inform understanding of this effect.

3.8 More research to demonstrate the occurrence of gradual peat mass movement would help to inform attempts to restore peat in some locations (such as at eroding edges of peat masses) and aid interpretation of surface subsidence studies.

Key question: b) what species of plant are peat- forming and what are their physical (hydrological and other) requirements?

- Peat forms where decomposition is retarded by waterlogging, so plant species which are found in peat are those which tolerate wet conditions and form wetland communities (Boudreau & Rochefort, 1998 [1++]); (Buttler *et al*, 1998 [1++]); (Campeau & Rochefort, 1996 [1++]); (Grosvernier *et al*, 1997 [1++]); (Komulainen *et al*, 1999a [2+]); (Holden *et al*, 2011 [2++]); (Carroll *et al*, 2009 [2++]); (Clymo & Reddaway, 1971 [2+]); (Malmer *et al*, 1994 [3+]). There are no studies that refute it.
- Blanket peat is typically composed of a variable mixture of remains of *Sphagnum* spp. (mainly *S. 'imbricatum'* which is now either *S. affine* or *S. austinii*), *Eriophorum* spp., dwarf shrubs, unidentified organic matter and Molina *caerulea*, the balance of which varies down the peat profile and between sites over small scales. (Chambers *et al*, 2007b [3+]);

(Chambers *et al*, 2007a [3+]); (Malmer *et al*, 1994 [3+]) and supported by (Mackay & Tallis, 1996 [3-]). There are no studies that refute it.

- High water tables facilitate the growth and increase the abundance of *Sphagnum*. (Boudreau & Rochefort, 1998 [1++]); (Campeau & Rochefort, 1996 [1++]); (Grosvernier *et al*, 1997 [1++]); (Komulainen *et al*, 1999a [2+]); (Carroll *et al*, 2009 [2++]) and supported by (Rochefort *et al*, 1995 [1-]); (Burtt & Hawke, 2008 [3-]); (Mackay & Tallis, 1996 [3-]). There are no studies that refute it.
- *Calluna vulgaris*, and other moorland plants of drier habitats, do not form blanket peat on their own, without the presence of *Sphagnum* or *Eriophorum* of other wetland plants. (Gunnarsson *et al*, 2008 [2++]); (Chambers *et al*, 2007b [3+]) and supported by (Mackay & Tallis, 1996 [3-]). There are no studies that refute it.
- *Molinia* can form peat on its own. (Chambers *et al*, 2007a [3+]); (Chambers *et al*, 2007b [3+]). There are no studies that refute it.

3.9 The evidence for *Molinia* as a peat-forming species is weak, and subject to differing interpretations of the data. More research on this topic would be valuable to understand the importance of *Molinia*-dominated blanket peat to carbon sequestration.

3.10 There is some evidence present in the topic review to suggest that the species found in contemporary peat macrofossil deposits approximate to NVC communities now defined as blanket bog and associated vegetation types. (Chambers *et al*, 2007a [3+]); (Chambers *et al*, 2007b [3+]) and supported by (Mackay & Tallis, 1996 [3-]). However, this data has not been digitised and analysed, and multivariate analysis for trends over time/depth would help to reveal more subtle patterns relating vegetation change to accumulation rates and management indicators.

Key question: c) what factors (management, atmospheric deposition and climatic) affect the hydrological, structural and floristic status and composition of blanket bog, and leads to its degradation?

Afforestation

- Ploughing and planting coniferous trees on peat lowers the peat water table and causes peat surface subsidence and compaction. (Shotbolt *et al*, 1998 [2++]); Anderson *et al*, 2000 [1++]) and supported by (Murphy, 2008 [3-]). There are no studies that refute it.
- Increasing time under forestry plantation results in greater changes in the understory community composition making it less similar to typical blanket bog vegetation. (Sheridan, 2008 [1++]) and supported by (Murphy, 2008 [3-]). There are no studies that refute it.
- Afforestation of blanket peatlands impacts negatively on blanket bog bird communities of high conservation value both in, and adjacent to, plantation areas. A single review study supports this statement (Stroud *et al,* 1988 [4]).
- Afforestation reduces methane emissions from peatlands and increases short-term carbon sequestration (Worrall *et al*, 2010 [2+]). There are no studies that refute it.

3.11 The impact of afforestation of methane emissions from peatland illustrates how management which causes loss or degradation in some functions may result in improvements in others. The short-term increases in rates of capture of atmospheric carbon may not be offset in the longer term by ongoing losses from a bog as it dries and subsides. To understand the full greenhouse gas impact of afforestation of peatlands would require a full life-cycle analysis, spanning centuries to consider many afforestation and felling cycles, and which includes the carbon impact of avoided fossil fuel use and the likely longevity and fate of wood products, as well as peat carbon loss.

3.12 The contention that afforestation impacts on bird populations of blanket mires is supported by a review which references many studies. It mentions ongoing work on forest edge effects on blanket bog birds, these results and other studies may have been published since the search criteria produced the reference master list.

3.13 Additional literature review is required to affirm and update the Evidence statement above.

Peat cutting

3.14 It was not possible to develop any Evidence statements from the literature reflecting peat cutting as there was insufficient evidence identified by the topic review. There is little evidence available to this topic review on the impact of peat cutting on the hydrology and other functions of peatlands. One laboratory study indicates that bare peat in peat cuttings initially dries out rapidly when water tables are low, but then remains stable, whereas dwarf-shrub vegetated peat continues to dry out (Farrick & Price, 2009 [2+]).

3.15 There is weak evidence (Ardron, 1999 [3-]) that there are distinctive plant communities between uncut blanket bog, in peat cuttings and at the boundary of cuttings and no evidence was reviewed that indicated impacts of peat cutting on many other functions. The weakness of the evidence base for the impact of peat cutting (rather than subsequent natural re-vegetation) may be based on the assumption that peat cutting will result in total loss of most peatland functions. Or be based on the view that upland peat cutting is no longer common practice, except for small-scale domestic purposes which are unlikely to be studied.

3.16 A more extensive literature search on the impacts of peat cutting on the hydrology and other properties of peatlands may produce evidence from technical studies designed to facilitate peat extraction, which were not identified by the search criteria of this topic review.

Drainage

- Drainage of blanket peatland lowers the overall water table compared to undrained peatlands, in a changing pattern relating to the location of the grips (Stewart and Lance,1991 [2++]); (Holden *et al*, 2011 [2++]); (Wallage & Holden, 2011 [2+]); (Anderson *et al*, 1995 [1++]); (Coulson *et al*, 1990 [2++]) and supported by (Murphy, 2008 [3-]). There are no studies that refute it.
- The impact of drainage on the response times for storm hydrographs (flashiness) is not consistent between studies. A total of 2 studies showed higher flashiness in (possibly the same) drained catchments (Holden *et al*, 2006 [2+]); (Robinson, 1985 [2+]) while a further study indicated no differences in flashiness (Grayson & Holden, 2012b [2++]), in a different catchment. This topic review could not compare the topography and drainage in these areas.
- Drained blanket peatlands have less overland flow than intact peatlands. (Holden *et al*, 2006 [2+]). There are no studies that refute it.
- Drained peatlands have a higher density and volume and larger size of peat pipes than undrained peatlands. (Holden, 2005a [2++]); (Holden, 2006 [2++]). There are no studies that refute it.
- Drained blanket peatlands have higher concentrations of DOC in their peat water. (Bussell *et al*, 2010 [1++]); (Wallage *et al*, 2006 [2+]); (Gibson *et al*, 2009 [2+]). There are no studies that refute it.
- Drained peatlands have a lower frequency or abundance of *Sphagnum* and *Eriophorum* spp., and a higher frequency or abundance of lichens or grasses, especially close to the drain. (Stewart and Lance,1991 [2++]); (Coulson *et al*, 1990 [2++]); (Bellamy *et al*, 2012 [2+]). There are no studies that refute it.
- Drained peatland may show higher or lower abundance of *Calluna* adjacent to grips, the response varying between sites. One study showed an increase in *Calluna* vigour (Stewart and Lance,1991 [2++]) while another showed a reduction (Coulson *et al*, 1990 [2++]). Other site factors (altitude, grazing) may be interacting to influence this response.

- Moorland drains on steep slopes (>4^{o}) tend to erode, while those on gentler slopes tend to infill, and there is more erosion at drain confluences than along lengths. (Holden *et al*, 2007 [2+]). There are no studies that refute it.
- Drained blanket peatlands emit less methane than undrained ones. (Bussell *et al*, 2010 [1++]); (Worrall *et al*, 2010 [2+]). There are no studies that refute it.

3.17 There is one study (Bussell *et al*, 2010 [1++]) which suggests that while there is weak evidence that peatland drainage increases gross respiration (including plant roots) there is no difference in net ecosystem respiration between drained peatlands and undrained peatlands. Another study (Worrall *et al*, 2010 [2+]) suggests that the drained peatlands emit more CO_2 than undrained peatlands. The former study took into account magnitude of impacts and rejected poorer quality studies, while the latter assessed more studies, but only examined direction of change and did not quality-assess studies.

3.18 The evidence shows that drainage increases DOC concentrations in soil water, suggesting that this may be an important pathway for carbon loss following drainage, yet there were no studies available to compare the impact of drainage on DOC export from blanket peatland catchments.

3.19 Further review or research into the impact of drainage on DOC loss would indicate the importance of this as a pathway for carbon loss from drained peatlands.

Atmospheric deposition of pollutants

- High past rates of deposition of acidic sulphur compounds will have slowed the growth rate of several typical blanket bog *Sphagna*. (Ferguson *et al*, 1978 [1+]).
- High levels of dry atmospheric deposition of ammonia will alter *Sphagnum* communities to remove some species of *Sphagnum* completely, or increase ‘undesirable’ nutrient-tolerant species such as *S. fallax*, and can damage the health of plants of drier moorland (*Calluna vulgaris* and *Cladonia portentosa*), while wet deposition of ammonium reduced cover of one *Sphagnum* species. (Sheppard *et al*, 2011 [2++]). There are no studies that refute it.

3.20 The literature analysed for this topic review represents a few key papers relating to the impact of air pollution on semi-natural habitats. A review of air pollution (NEGTAP, 2001) noted that while sulphur pollution impacts had ameliorated, bog communities had seen increases in plants associated with higher N requirements. A more recent UK-wide project (Review of Transboundary Air Pollution – RoTAP, 2012) has examined the impacts and extent of acidification, eutrophication, heavy metals and low-level ozone pollution, including impacts on semi-natural vegetation. This report concluded that declining species richness in moorlands, and replacement of pollution sensitive bryophytes with more pollution-tolerant communities was a relatively recent phenomenon. However, the links to pollutant deposition were correlatory, and causal relationships require further experimental studies to establish. It notes that while 40-50 % of the area of UK bogs are subject to N deposition that exceed critical load values (10 kg N ha^{-1} yr^{-1}) vegetation responses to deposition are a continuum, and do not take the form of a critical threshold. However, they recognise that ammonia gas appears to be more damaging to moorland vegetation than wet ammonium deposition and a new threshold is identified of 1 µg m-3 above which impacts on bryophytes and lichens would be expected. While some 69% of the UK is identified as being above this threshold, the majority of English uplands appear to be below it, suggesting that N pollution should not present an insurmountable obstacle to bog restoration.

Changes in semi-natural vegetation

- Blanket peatlands dominated by *Calluna vulgaris* have more frequent and dense peat pipes, and higher macropore flow lower in the soil, which increases with ongoing high rainfall, unlike that for peat under *Eriophorum*, *Sphagnum* or bare ground. (Holden, 2005b [2+]). There are no studies that refute it.

- *Sphagnum*-dominated blanket bog vegetation has slower rates of overland flow during storm conditions than blanket bog dominated by *Eriophorum* or a mix of *Eriophorum* and *Sphagnum.* (Holden *et al*, 2008 [2++]). There are no studies that refute it.
- Both *Eriophorum vaginatum*-dominated and *Calluna vulgaris*-dominated vegetation have similar macropore flow at deeper layers (10-30cm) which is lower than in peat under *Sphagnum*-dominated vegetation. (Holden, 2005b [2+]); (Holden, 2009a [2+]); (Holden *et al*, 2001 [2++]). There are no studies that refute it.
- Blanket peat dominated by *Calluna vulgaris* tends to have higher DOC export through its drainage waters (Worrall *et al*, 2011 [2++]), and higher DOC concentrations in its grips (Armstrong *et al*, 2008 [2-]); (Armstrong *et al*, 2010 [2+]), than blanket peat dominated by other vegetation. There are no studies that refute these findings.
- A single laboratory-based study (Green *et al*, 2011 [2++]) suggests that blanket bog vegetation dominated by either *Calluna* or *Eriophorum vaginatum* is likely to have larger annual methane emissions, and larger overall contribution to global warming, than those dominated by *Sphagnum papillosum*, and this effect is likely to be exacerbated by warmer climates. No studies refute this statement but this has yet to be proved in the field.

3.21 There are no studies available to this topic review that indicate the impact on blanket peat function of dominance of *Molinia caerulea*, with the exception of two studies whose data suggest that it is capable of forming peat, based on macrofossil analysis. *Molinia* is seen as undesirable in terms of biodiversity, but this topic review found no evidence regarding whether its dominance may be beneficial or detrimental to functions such as maintaining water quality, ameliorating runoff or Green House Gas (GHG) fluxes. Further review or research would help to inform the wider impacts of the current efforts to control this species.

3.22 There were also no studies that allowed a comparison of the impact of transpiration by dry moorland vascular plants on peat hydrological function. There is one study (Farrick & Price, 2009 [2+]) which indicate that dwarf shrubs reduce peat moisture content lower down the peat profile than is observed in bare peat. A further study (Clay *et al*, 2009) reported significant increases in water table following removal of moorland vegetation (presumably *Calluna*) by burning, and that rotationally burnt plots had higher water tables than plots with no burning for 50 years, but did not provide details of the vegetation type, structure or biomass, or clearly describe the number of years since the most recent burn. Since high water tables are needed to preserve peat, lowering of water tables by vascular plant transpiration might be expected to accelerate peat decomposition. Conifers (which like *Calluna* are evergreen vascular plants) have been shown to lower water tables and increase subsidence (Shotbolt *et al*, 1998 [2++]). If drying of peat by vascular plant transpiration were better understood it could help to explain the relationships observed between *Calluna* dominance and DOC and inform management to reduce carbon loss, water colour and improve bog condition in terms of biodiversity.

Gullying and hagging

- Gully erosion of blanket peatlands in northern England accelerated during the late 18^{th}/early 19^{th} centuries. (Phillips *et al*, 1981 [2+]) and supported by (Mackay & Tallis, 1996 [3-]). There are no studies that refute it.
- Severity of gullying and hagging is associated with higher, flatter areas, with reticulate (type 1) erosion on flatter tops, and linear (type 2) erosion on more sloping ground (Phillips *et al*, 1981 [2+]); (McHugh *et al*, 2000 [2+]) and supported by (Wishart and Warburton, 2001 [3-]). There are no studies that refute it.
- Water table in peatlands is lowered by gully/hagg erosion. (Holden *et al*, 2006 [2+]) and supported by (Mackay & Tallis, 1996 [3-]). There are no studies that refute it.

Erosion of bare peat

- Bare peat surfaces can rapidly recede vertically (up to 62 mm per year). A total of 5 studies (4 from the Peak District and one case study of an eroding peat flat) support this statement: (Phillips *et al*, 1981 [2+]); (Worrall *et al*, 2011 [2++]); (Warburton, 2003 [2+]), supported by (Anderson *et al*, 1995b [2-]); (Buckler, 2007 [2-])However two studies, comprising a national monitoring survey of gully erosion over 2 years (McHugh *et al*, 2000 [2+]) and a case study of the Cheviot Hills looking at erosion over 5 or more decades (Wishart and Warburton, 2001 [3-]) found no detectable changes in erosion features in the short or long term.
- Overland flow over bare peat is faster than over vegetated peat. (Holden *et al*, 2008 [2++]) and no studies that refute it.
- In drought conditions bare peat loses water from its surface rapidly, but retains it at depth. (Farrick & Price, 2009 [2+]) and there are no studies that refute it.
- Single studies show that bare peat loses significant amounts of POC, moderate amounts of DOC, does not emit much CO_2 (Worrall *et al*, 2011 [2++]), and has low biological activity (Caporn *et al*, 2007 [1+]). No studies were considered that refute these findings.

3.23 The rate of erosion loss from peat in gullies, edges of peat masses and from other bare peat areas varies with location, and the prevalence of studies in the Peak District may give a bias towards more actively eroding sites, which are more likely to be studied since they are likely to benefit most from restoration management. Erosion rates in a selection of gullies studied by McHugh *et al,* (2000 [2+]) and supported by Wishart and Warburton (2001, [3-]) in the long-established gullies were low, and this suggests that not all gullies may need to be blocked to ensure the stability of the peatland.

Key question: d) what interventions are required to restore a degraded blanket bog to a functioning and active blanket bog system with abundant peat-forming species, and over what timescale?

Deforestation

- Felling coniferous trees on blanket peatland is more likely to result in blanket bog vegetation recovery where the plantation is younger. (Sheridan, 2008 [1++]); supported by (Murphy, 2008 [3-]). There are no studies that refute it.
- One study (Sheridan, 2008 [1++]) shows that felling trees to waste, and disposing of waste on site need not prevent recovery towards blanket bog vegetation and that blanket bog vegetation will recover more quickly, and to more characteristic vegetation, where the ground is flatter, wetter and where forest residues are thinner. There are no studies that refute these statements.

3.24 The impact of deforestation on carbon and GHG budgets is reported as being unlikely to result in improved C or GHG flux (Worrall *et al*, 2010 [2+]) but this intervention has the lowest effective sample size of all analyses in this study and may represent short-term measurements. A further study (Komulainen *et al*, 1999a [2+]) applied both felling and drain blocking treatments, and so the impact of these cannot readily be separated. Further research is needed to elucidate the impacts of deforestation on GHG and C flux in peatlands, but would also benefit from comparison with longer term analysis of the impact of peatlands in a forested condition.

3.25 Given that afforestation has been seen to lower water tables, deforestation would be expected to raise water tables, thus preventing peat decomposition and providing conditions for recovery of blanket bog communities and functions. Additional review or research might help to indicate the extent to which felling alone is required to restore bog functions, and where additional interventions are required.

Re-vegetation of bare peat

- Re-vegetation of bare blanket peat is possible, using *Calluna vulgaris*, grasses, or *Eriophorum angustifolium*. (Caporn *et al*, 2007 [1+]); (Skeffington *et al*, 1997 [1+]); (Richards *et al*, 1995 [1+]); (Bridges, 1985 [2++]); (Sliva & Pfadenhauer, 1999 [1++]) and supported by (Anderson *et al*, 1995b [2-]); (Anderson *et al*, 2011b [2-]); (Buckler, 2007 [2-]); (Gore & Godfrey, 1981 [2-]); (Tallis & Yalden, 1983 [2-]). There are no studies that refute it.
- Addition of both lime and fertiliser enhances the success of nurse grass, *Eriophorum angustifolium* and *Calluna vulgaris* establishment. (Caporn *et al*, 2007 [1+]); (Richards *et al*, 1995 [1+]); (Skeffington *et al*, 1997 [1+]); (Bridges, 1985 [2++]); (Sliva & Pfadenhauer, 1999 [1++]) and supported by (Anderson *et al*, 1995b [2-]); (Buckler, 2007 [2-]); (Gore & Godfrey, 1981 [2-]). There are no studies that refute it.
- Plants of lowland situations, such as agricultural grasses or legumes, are less likely to germinate and survive than those found naturally in uplands. (Bridges, 1985 [2++]); supported by (Gore & Godfrey, 1981 [2-]); (Buckler, 2007 [2-]). There are no studies that refute it.
- Re-vegetation of bare peat, along with interventions to aid re-vegetation, can result in increased rates of CO_2 emissions compared with bare peat. (Caporn *et al*, 2007 [1+]); Worrall *et al*, 2011 [2++]). There are no studies that refute this statement.
- Bare peat, following re-vegetation, shows a related increase in the activity and abundance of soil microbes. (Caporn *et al*, 2007 [1+]). There are no studies that refute it.
- Re-vegetation of bare peat with grasses and *Calluna vulgaris* will reduce, but will probably not reverse, net loss of carbon from hydrologically unrestored peatlands. (Worrall *et al*, 2011 [2++]); (Worrall *et al*, 2010 [2+]). There are no studies that refute it.
- Re-vegetation of bare peat results in reduction of POC loss (Worrall *et al*, 2011 [2++]); (Worrall *et al*, 2010 [2+]). There are no studies that refute it.
- Re-vegetation of bare peat with nurse and moorland grasses, and *Calluna* will not reduce DOC loss. (Worrall *et al*, 2011 [2++]); supported by (Anderson *et al*, 2011b [2-]). There are no studies that refute it.

3.26 There are two lower-quality studies that report that applying geojute to bare peat encourages more rapid development of cover (Anderson *et al*, 2011b [2-]); (Buckler, 2007 [2-]). Further research, or data from additional sources, would strengthen the evidence clarifying to what extent geojute application; a potentially expensive intervention should be adopted.

Re-establishment of *Sphagnum*

- Current atmospheric and climatic conditions in English blanket peatlands are not prohibitive to the growth of *Sphagnum*. A total of 7 studies indicate recent increases in *Sphagnum* abundance or widespread distribution with no climatic or depositional effects: (Clymo & Reddaway, 1971 [2+]); (Carroll *et al*, 2009 [2++]); (O'Reilly, 2008 [2++]) supported by (Burtt & Hawke, 2008 [3-]); (Anderson *et al*, 2011a [2-]); (Hinde *et al*, 2010 [2-]); (Caporn *et al*, 2006 [2-]).
- *Sphagnum* reintroduction is more successful where water table is raised, humidity is high, and with either shade fabric, nurse vegetation or mulch, and where *Sphagnum* diaspores were collected from the top 10 cm of intact bog, but this depends also on the species used and the physico-chemical conditions of the peat substrate (Boudreau & Rochefort, 1998 [1++]); (Bugnon *et al*, 1997 [1+]); (Buttler *et al*, 1998 [1++]); (Campeau & Rochefort, 1996 [1++]); (Groeneveld *et al*, 2007 [1++]); (Grosvernier *et al*, 1997 [1++]); (Rochefort *et al*, 1995 [1-]); (Rochefort *et al*, 2003 [1++]) , (Grosvernier *et al*, 1995 [1++]); (Robroek *et al*, 2009 [1+]); (Ferland & Rochefort, 1997 [1++]). There are 3 studies that found contrasting results: one found no relationship between recovery of *Sphagnum* and soil moisture (Chirino *et al*, 2006 [1++]); another found no benefit of straw mulch application (Rochefort

& Campeau, 2002 [1++]), and another found higher water tables detrimental due to regular flooding (Tuittila *et al*, 2003 [2+]).

3.27 The application of mulches, nurse plants or shade fabric has been demonstrated in the studies above to reduce or counteract the impact of lower water tables to aid *Sphagnum* recovery, in either laboratory experiments on in cut-over Canadian raised bogs. However, there was no evidence identified in this topic review to indicate whether natural recovery of *Sphagnum* or the establishment of newly-planted *Sphagnum* could occur in areas of degraded blanket bog with low water tables, but high humidity, due to mulching, rainfall, nurse crops etc. Given the water retentive properties of both living and dead *Sphagnum* , and difficulties in restoring water tables in severely eroded peatlands, demonstration of this effect on English blanket bogs would be useful to inform practical conservation measures.

3.28 A single lower-quality study (Caporn *et al*, 2006 [2-]) indicates that *Sphagnum* reintroductions to upland *Eriophorum* blanket bog can persist unaided for several decades. The long-term prospects for reintroduced *Sphagnum* on English Blanket peatlands would inform its management, but opportunities to study this on long-established reintroduction trials are likely to be limited. Given the medium-term success of *Sphagnum* reintroductions seen in Canadian cut-over bogs, a lack of knowledge of the long term impacts should not prevent reintroduction programmes for English blanket peatlands, but indicate the importance of establishing accurate monitoring, with controls.

Control of 'undesirable' semi-natural vegetation

- The dominance of *Molinia caerulea* can be reduced by vigorous cutting, grazing and herbicide treatments. (Milligan *et al*, 2004 [1+]); (Milligan *et al*, 1999 [1+]); (Milligan *et al*, 2003 [1++]); (Todd *et al*, 2000 [1++]); (Marrs *et al*, 2004 [1++]); (Ross, 2011 [2+]). There are no studies that refute it.
- Spring burning does not reduce the dominance of *Molinia*, unless in combination with a more successful approach such as those mentioned above. (Todd *et al*, 2000 [1++]); (Marrs *et al*, 2004 [1++]). There are no studies that refute it.

3.29 There were no studies which sought to control the over-dominance of other moorland species. Given the association between *Calluna vulgaris* and piping, DOC, methane and CO_2 emissions, and potential drying impact of this species on blanket peat soils, and its high extent of dominance in blanket peatlands (which represents a cause of floristic degradation), more review or research would be required into how best to control this species, if hydrological, geochemical and biodiversity functions are to be restored.

3.30 There were also no studies examining the management of over-dominance by *Eriophorum vaginatum*, which may also exclude positive indicator species and therefore represent floristic degradation. However, presence of this species seems to be associated with loss of fewer functions in peatland, and therefore represents less serious degradation.

3.31 To date research on control strategies for *Molinia caerulea* are often accompanied by efforts to re-establish *Calluna vulgaris*. The studies examined in this review have only considered vegetation responses, and it would seem appropriate to examine the impact of successful control of *Molinia*, and replacement with *Calluna*, on the full range of blanket bog hydrological functions. However, it should be noted that some of the research quoted in this review is likely to have been conducted on sites with shallower (<40cm) peat, and may not represent true blanket peatlands.

Gully blocking

- Blocking gullies with plastic piling dams, stone or wooden barriers trap peat sediment and enable colonisation by plants, particularly *Eriophorum angustifolium*. This statement is supported by 2 studies: (Evans *et al*, 2005 [2++]) and (Burtt & Hawke, 2008 [3-]). There are no studies that refute it.

3.32 This topic review has found little evidence of the hydrological impacts of gully blocking. Given that the evidence of rapid gully erosion may be biased towards actively eroding sites, and many gullies may not be eroding rapidly (McHugh *et al*, 2000 [2+]) and may be long-established Phillips *et al*, 1981 [2+]) supported by (Mackay & Tallis, 1996 [3-], further investigation of the impact of gully blocking on the wider functions of peatlands, especially those that are more intact, would help to forestall future problems. A review of how water drains from peatlands, if not through gullies and streams, would be a valuable addition to this.

Key question: e) does the blocking of artificial drainage channels (grips)on degraded blanket bog result in a functioning and active blanket bog with abundant peat forming species and representative bog flora and fauna. If so, do all drains require to be blocked?

- There is mostly weak and some stronger evidence that grip blocking increases the abundance of wetland plant species. (Holden *et al*, 2011 [2++]); (Komulainen *et al*, 1999a [2+]); (Lavoie *et al*¸2005 [2+]); (Glendinning, 2012 [2+]); (Bellamy *et al*, 2012 [2+]) supported by (Anderson *et al*, 2011a [2-]) and (Vasander *et al*, 2003 [2-]). There are no studies that refute it, but much of the evidence is based on general description rather than experimental interventions, or from poorly-replicated case studies, or could be related to several treatments.
- Two studies (Ramchunder *et al*, 2012 [2++] & Carroll *et al*, 2012 [2++])) found that grip blocking increases invertebrate abundance and diversity but a further, lower quality, study, found no significant differences in invertebrate communities at blocked and open drains (Phillips, 2008 [2-]).
- Grip blocking raises the water table, but not to the level found in intact peatlands. (Holden *et al*, 2011 [2++]); (Wallage & Holden, 2011 [2+]); (Wilson *et al*, 2010 [2++]); (Armstrong *et al*, 2010 [2+]); (Komulainen *et al*, 1999a [2+]); and supported by (Anderson *et al*, 2011a [2-]); (Armstrong *et al*, 2008 [2-]). However, a further 2 studies found that grip blocking had no detectable impact on water tables (Jonczyk *et al*, 2009 [3+]); (Wilson *et al*, 2011 [2++]).
- There is mixed evidence that blocking reduces the flashiness of flood hydrographs. A total of 2 studies recorded lower flashiness in blocked catchments (Grayson & Holden, 2012a [2++]); (Wilson *et al*, 2011 [2++]) while another study found no impact of blocking on hydrograph flashiness (Grayson & Holden, 2012b [2++]).
- Grip blocking reduces overall water yield and catchment 'efficiency'. (Gibson *et al*, 2009 [2+]); (Grayson & Holden, 2012a [2++]); (Wilson *et al*, 2010 [2++]). There are no studies that refute it.
- A single study found that grip blocking increased base flow (Wilson *et al*, 2011 [2++]). There are no studies that refute this statement.
- Grip blocking increases surface hydraulic conductivity in peat and reduces surface bulk density. (Wallage & Holden, 2011 [2+]); (Holden *et al*, 2011 [2++]). The study reporting decreased hydraulic conductivity, however, took no measurements prior to blocking, and represented only 3 sites, so pre-existing differences in bulk density cannot be ruled out.
- The evidence relating total DOC export from catchments to blocking suggests variable responses. Two studies found that blocking grips slightly reduces the DOC export from the catchment: (Wilson *et al*, 2011 [2++]); (Wilson *et al*, 2011b [2++]) while two further studies found inconsistent responses (reducing and increasing) among different blocked catchments (Gibson *et al*, 2009 [2+]); (Grayson & Holden, 2012a [2++]).
- There is no clear pattern in the response of stream DOC/colour concentrations. There are 3 studies showing lower DOC in stream/drain waters in blocked compared to openly drained sites (Anderson *et al*, 2011a [2-]); (Armstrong *et al*, 2008 [2-]); (Armstrong *et al*, 2010 [2+]) 3 studies showed no change (Jonczyk *et al*, 2009 [3+]; Wilson *et al*, 2011 [2++]; Grayson & Holden, 2012b [2++]); one showing no change or variable responses

(Gibson *et al*, 2009 [2+]) and 1 study showed higher DOC concentrations in these situations (Wilson *et al*, 2011b [2++]).

- Grip blocking does not reduce DOC and water colour in soil water. A single study, incorporating 3 studies (Bussell *et al*, 2010 [1++]) supports this statement, while a single study (Wallage *et al*, 2006 [2+]) found reduced DOC in peat soil water in blocked sites.
- Four studies found that grip blocking resulted in lower POC export: (Grayson & Holden, 2012a [2++]); (Wilson *et al*, 2011b [2++]); (Wilson *et al*, 2011 [2++]); (Vassander *et al,* 2003 [2-]) while one further study suggests no significant impact (Grayson & Holden, 2012b [2++]).
- Grip blocking reduces CO_2 emissions. (Worrall *et al*, 2010 [2+]); (Komulainen *et al*, 1999a [2+]); (Vasander *et al*, 2003 [2-]). However, the second paper is included in the first, which concludes that there is a low probability of improvement in carbon budget on grip blocking. CO_2 emissions are almost as likely to remain unchanged on grip blocking as to reduce.
- Grip blocking increases methane emissions. (Bussell *et al*, 2010 [1++]); (Worrall *et al*, 2010 [2+]); supported by Vasander *et al*, 2003 [2-]). There is one study (Green *et al*, 2011 [2++]) however, that suggests that high and constant water tables would not increase CH_4 over more fluctuating ones.
- The type of grip infill used is likely to strongly influences the methane emissions and carbon balance of the grip (Green *et al*, 2011 [2++]) with heather brash infill and re-profiling of grips leading to higher emissions of both CO_2 and methane compare with open water or *Sphagnum* mats. This impact has yet to be proved in the field.
- Using peat dams to block grips provides comparable or better success rates at retaining water to more expensive solutions. Additional analysis of data is presented in (Armstrong *et al*, 2010 [2+]); (Armstrong *et al*, 2009 [2+]) and supported by (Armstrong *et al*, 2008 [2-]);. However, there are no studies that refute it.
- A single study indicates that grips on shallow slopes are more likely to infill and re-vegetate and less likely to erode (Holden *et al*, 2007 [2+]). There are no studies that refute it.

3.33 The evidence that blocking grips reverses the changes in vegetation seen in blanket bogs following drainage is weak. This is related more to the paucity of studies examining this effect alone, as well as the studies possibly not covering a long enough timescale to detect changes. Much effort has been expended in grip blocking on blanket peatlands that are valued for their biodiversity, and it would be hoped that some of the changes affected would be picked up by detailed monitoring by moorland restoration projects, of SSSIs or of agri-environment schemes. A more directed search is required to establish whether this monitoring data exists, and, if not, detailed vegetation monitoring of blocked and comparative monitoring of unblocked sites should be established as a priority.

3.34 This topic review has indicated that many of the hydrological and geochemical responses of blanket peatlands to grip blocking are hard to predict from our current knowledge, and that there may be other factors at play that exert a greater level of control. It is easy to confuse interpretations of DOC concentrations in water in soil, grips, stream samples and at catchment outflows and catchments may be very different in size and in the range of influences they reflect. Studies are often only short-term whereas hydrological and geochemical process responses are likely to develop over much longer periods of time. A robust understanding of a range of land management and restoration impacts on hydrology, DOC and POC export would require a widespread programme over several years, and replicated at the catchment scale, with monitoring of other potentially important factors, multivariate statistical approaches, possibly including monitoring on sub-catchments, and replicated application of catchment scale interventions, with comparison to controls.

3.35 As an alternative, larger scale (national) correlatory studies of water colour, along with extent of gripping in catchments, extent of grip blocking, extent of other factors (erosion, vegetation, grazing, burning etc.) could be subjected to multivariate analysis. This would require consistent and improvement monitoring of upland vegetation, and acquisition of hydrological data.

3.36 In many instances, however, the apparent disagreement in the research is not related to the direction of change, but rather to the significance of it. 'Variable' responses to grip blocking, if treated as true replicates, might either simply indicate no significant change (due to error variability), or may reflect the significant influence of another management. Differences in the results may also relate to the scale of the catchments used in the studies. These results indicate that differences in the catchment flashiness response to grip blocking are very likely to be influenced by local topography.

3.37 Data on the impact of grip blocking on CO_2 emissions seems particularly weak, with the systematic review of Bussell *et al*, (2010 [1++]) having found no qualifying studies.

Key question: f) are there are conditions where it is not feasible to completely restore a degraded blanket bog to a fully functioning bog system with its representative flora and fauna, and if so what is likely to prevent their full recovery?

3.38 There is no evidence in this review to suggest any areas of peat are completely un-restorable.

3.39 This does not mean that restoration of blanket bog is always desirable, affordable or realistic. Constraints to restoration can arise from social, political and economic factors, and the time required for full restoration are as yet unknown and may be prohibitive. The ecological niches for blanket bog species may not be present, but these can, and are, often adjusted by management interventions many of which are reviewed here. Climatic factors have constrained the initiation of blanket bog formation in the past, and may constrain initiation of new bog now, but these do not predict the survival of existing bogs or restoration of damaged peatlands. This review has shown that blanket bogs affect local hydrology and other conditions in ways that will promote blanket bog survival, and potentially reduce climatic impacts.

3.40 This topic review has taken the current distribution of blanket peat to indicate the area of former, and potentially restorable, blanket bog. However, this may not be the case if the blanket peat has moved. Gradual creep of peat, towards edges of hill slopes, may make it all but impossible to restore these eroding edges, since the hydrological conditions that formed the peat may only be present in the peat's initial location. Furthermore, peat that has been subject to major topographic changes in land form (landslips etc.) may be beyond restoration due to the new prevailing conditions. Development of buildings, infrastructure and quarrying may make restoration of bog difficult and/or undesirable.

Key question: g) are there any wider environmental impacts resulting from the restoration of degraded blanket bogs?

3.41 Because our definition of degradation was a loss of peatland function, many of the wider impacts of restoration have been considered in the sections above. Others, relating to economic, cultural, and social or relating to food production are outside the scope of this review.

3.42 The issue of different management and activities on blanket peatland GHG flux has been considered throughout this review, with the evidence largely drawn from a systematic review, (Bussell *et al*, 2010 [1++]) and a meta-analysis (Worrall *et al*, 2010 [2+]). These provide an overall picture of intact blanket peatland being a net carbon sink but a net source of greenhouse gases due to methane emissions. Emissions of methane are reduced following managements that lower the peat water table (such as drainage or afforestation), but this is accompanied by increases in carbon dioxide emissions. However, the greenhouse gas impact of drainage may be beneficial overall, but may also increase losses through non-gaseous routes (DOC, POC) and the fate of carbon lost by these routes is not clear. Deforestation stops the rapid carbon capture by trees, but will also help to prevent the ongoing loss of peat carbon, provided bogs can be restored, but is unlikely to result in short term C benefits. Re-vegetation of bare peat will result in carbon benefits over the bare peat, especially reducing POC losses, but may not stop ongoing loss of DOC from the peat (Worrall *et al*, 2011 [2++]), following the initial capture of atmospheric C by the new vegetation. Re-wetting a peatland may help to prevent carbon loss as CO_2 from the peat, but will increase methane emissions, at least over the short term, but increased emissions may be amenable to control through management of the vegetation (Green *et al*, 2011 [2++]).

Analysis of the functions of intact, degraded, and restored blanket bog

3.43 The evidence assessed in this topic review has been synthesised below to provide an evidence-based narrative, which describes the features and functions of intact blanket bogs, and how these change through both degradation and restoration. This narrative is referenced using hyperlinks in the text to the relevant information presented in Appendix 5: Analysis of evidence.

3.44 The evidence gathered by this review indicates that blanket bogs in their undisturbed state are systems which accumulate peat into a more or less permanently waterlogged layer called the catotelm, under high water table conditions. These bogs are dominated by wetland plant species, with *Sphagnum* mosses, *Eriophorum* spp. and variable levels of other associated plants including ericaceous dwarf shrubs, and it is their plant material that accumulates to form peat.

3.45 This situation is self-perpetuating in that the peat has low hydrological conductivity (water moves slowly through it) and this prevents any water captured from rainfall from escaping, helping to maintain the high water tables, and thereby form more peat, and support ongoing wetland vegetation. The high water table leaves little opportunity for infiltration of rain during storms and much rainfall runs off over the surface, with some also travelling down natural paths of low resistance within the peat, to form peat pipes. The speed at which the water runs off the intact peatland is also influenced by the vegetation, and a large component of *Sphagnum* mosses slows its flow into river channels. Water running from intact peatlands does not export large amounts of dissolved carbon and water colour. This may be because the runoff does not interact much with water trapped in the peat mass, or because the permanently waterlogged peat does not decompose rapidly, and DOC is not rapidly produced. However, the high water tables do encourage slow anaerobic decomposition of the peat material, and this is released by diffusion, bubbles or through plant tissues as methane – a powerful greenhouse gas.

3.46 Because blanket bogs are systems driven by the hydrological characteristics, any intervention that lowers the water table will change many of their functions and characteristics. Drainage can have strong localised effects on the water table, especially downslope of the drainage channels, due to the diversion of overland flow down the drain, rather than down the slope, and the erosive forces of the water lead to widening and deepening of these channels with loss of peat (and the carbon it stores) and increased inputs of sediments into streams. These drained peatlands also lose more dissolved carbon in their drainage waters.

3.47 The drains also result in local changes in vegetation with a loss of *Sphagnum* and an increase in plants that are more tolerant of drier conditions. The plants themselves also have an impact on the water table. *Sphagnum* mosses have no roots, but roots of *Calluna* or planted Picea sitchensis trees, where these are encouraged or planted, have roots that will extend into drier areas of peat and their impact is primarily to dry the peat. When peat becomes drier, it shrinks, physically, through loss of water, and chemically, as the peat material itself is broken down by microbes and the enzymes they produce. The changed vegetation will gradually alter the other vegetation components to be less similar to the initial bog vegetation, and will continue to deposit litter, but this fails to counteract the loss of peat from the lower layers. While there seems to be little difference in the loss of peat carbon as respired CO_2, increases in release of dissolved organic carbon, and water colour (its visible component), are a consistent feature of peatlands that have become dominated by dry-land adapted plants.

3.48 As the peat shrinks and humifies, it becomes denser, but also its hydrology changes. More water flows through large pores, perhaps opened by the roots or their drying effects, or as cracks associated with drainage itself, and over time these enlarge to become new peat pipes. When rainstorms fall on these altered peatlands, more water flows through these enlarged pores, with less over the surface, and can be transported down the drains, and, depending on the shape and size of the catchment and the configuration of the grips, flashy flow can increase. However, as water tables are drawn down by the drainage and by transpiration by the dry moorland plants that this encourages, the levels of methane emissions also reduce (by ~8mg CH_4 m^{-2} day^{-1}), but this is unlikely to offset the ongoing loss of carbon, although in half the instances studied it could improve the net balance of GHG emissions. Gullies that occur in peatlands can be hundreds of years old, and may be natural features, but have in some areas become so severe and interlinked that large volumes of peat have been lost. Where these areas are bare, due to overgrazing, wildfire or deposition of pollutants, the peat material is lost through physical erosion by wind and water, and this loss can be rapid. The remaining bare peat is a hostile place for the germination and survival of plants, being often highly acid, subject to extremes of temperature and humidity and subject to regular disturbance and rapid surface water flow, and supports little soil biological activity.

3.49 A severely damaged blanket bog can represent little more than an area of bare hagged peat, interspersed with channels of bare mineral soil that once underlay the peat. To restore an area that is this severely degraded to one that replicates the features and functions of an intact bog is a major challenge and most restoration activities only seek to control some of the least desirable processes. However, each of these activities can be seen as a step that brings the site closer towards its ideal, fully restored condition. The evidence in this topic review indicates that the hostility of bare peat to plants can be ameliorated by application of lime, fertiliser and stabilisation with geotextiles or brash, and that these techniques can provide a vegetation cover through seeding or transplanted plugs which will stop the majority of particulate carbon loss from the peat surface. However, this re-vegetation does not aim to restore the hydrological conditions for blanket bog, and the evidence indicates it can lead to more biological activity, and will not prevent loss of peat carbon in solution.

3.50 Drainage grips on flatter ground often infill without intervention. On steeper land, blocking grips and gullies helps them to trap sediments and infill and can raise the water table closer to that of the intact bogs. Peat dams are an effective method for blocking grips. Grip blocking encourages wetland bog plants and benefits invertebrates that are food for moorland birds. These blocks can also affect the water movement through the catchment, sometimes reducing flashy flow, and reducing loss of peat by erosion, but have variable impact on dissolved carbon loss. Blocking grips seems to reduce decomposition of the peat, with reduced production of DOC in the peat itself and possibly lower CO_2 emissions. Although the wetter peat has higher methane emissions than the drained peat, the pools formed behind the grips are probably not hotspots of methane emission.

3.51 Increasing the water table will facilitate the re-establishment of *Sphagnum*, too, with studies showing that different species seem to respond differently in a range of conditions, but also that providing some shelter, shade, and humidity can help. Despite studies that suggest severely sub-optimal conditions for *Sphagnum* in the English uplands, it is clear that at least some *Sphagnum*, whether pre-existing or reintroduced, can survive, and even widespread pollution problems can be ameliorated through changes in policy, management practices and development planning.

3.52 It may also be necessary to apply management to the vegetation itself to reduce the shading or drying impact of species, and restore the balance to promote more abundant wetland plants. Removing trees can be enough to start the process of gradual change towards blanket bog vegetation, but there are no reports of efforts to control *Calluna* dominance on peatlands, which would be likely to have similar impacts. Other wetland plants such as *Eriophorum vaginatum* and *Molinia caerulea* may also outcompete *Sphagnum* mosses, and *Molinia* can be controlled to some extent by intensive herbicide, cutting or grazing treatments, but it would be worth considering whether this would repay the effort, given that these plants are likely to be part of the ongoing cycle of vegetation change, over millennia, in blanket bogs, and support valuable functions such as peat formation and regulating water quality, even if they don't represent an idealised blanket bog community.

3.53 No studies have reported complete restoration to a fully functioning, active, blanket bog, comparable in its characteristics to an intact bog, from any degraded initial condition. This is perhaps not a surprise since the natural characteristics of bogs change over, tens, hundreds or thousands of years. However, it is apparent that for some functions at least, restoration is moving bogs, which have been affected by drainage, afforestation, management to deliver non-bog vegetation or other factors, closer towards the biological, hydrological and geochemical condition of intact bogs. There is no evidence in this review to suggest that we cannot restore blanket bog. Every restoration paper gives some cause for hope of eventual success. However, not all restoration techniques are successful and studies where all restoration treatments fail might be unlikely to be published.

3.54 Some important questions remain unanswered by this topic review. Our understanding of processes of erosion, gullying and carbon storage, and of where to apply restoration, would be improved by better knowledge of whether peat masses are subject to 'creep' under gravity. Better understanding of peat formation by *Molinia*, and of its other environmental impacts, might help temper our management to control this species. The peat macrofossil studies considered are invariably under-analysed and multivariate and community analysis of peat profiles could highlight currently obscure relationships between charcoal (burning), indicators of industrial pollution and crop pollen (human activity) and vegetation change in peatlands.

3.55 The evidence suggests that forestry on peatlands results in increased capture of atmospheric carbon, but this is based on short-term analysis incomparable with the timescales over which peatlands form. Longer term impact of forestry or deforestation on peatland carbon balance and GHG flux, would help inform management of afforested peatlands. Strategies to control the over dominance of bog vegetation by *Calluna* or *Eriophorum vaginatum*, could deliver better biological quality, as well as influencing water table.

3.56 Many factors appear to be affecting peatland hydrology and water quality at the catchment scale. The inconsistent evidence presented here suggests that greater reflection of spatial and topographic features, inclusion of more ecological factors at a greater level of detail, as well as management factors such as drainage or blocking, and coordinating studies across a wider range of widely representative catchments, would result in better predictive models of the impacts of management. Water quality impacts seem to be more driven by vegetation than by point interventions, and better understanding of both the mechanisms and interactions of this effect would help to develop mitigation strategies. Evidence for gaseous flux, especially relating to rewetting of peatlands, remains weak, and a coordinated monitoring programme would help us to understand and manage the GHG impact of peatland restoration.

3.57 Reintroduction of *Sphagnum* may still be frustrated to some extent but is not precluded by pollution. Further review or research into the impacts of atmospheric pollutants on wider bog plant communities and their interactions would indicate whether competition and pollutant deposition interact, and if this effect is amenable to management to favour the recovery of blanket bog vegetation. The hydrological impacts of transpiration by vascular plants, and of their removal, in bogs would seem to be a useful area of study that may explain many aspects of peatland degradation. Understanding the longer term impacts of re-vegetation of bare peat would help prioritise future restoration actions, and determining whether humidity in these situations can be managed to encourage *Sphagnum* recovery, even in low water table areas, could help them to recover further.

4 General discussion

4.1 The scope of this topic review has been very broad and has considered a wide range of different research papers. However, the search terms employed have resulted in a particular focus in some areas, and identified fewer studies in others. This is an inevitable outcome of restricting search terms, and should not affect the conclusions of the topic review in those areas where the evidence identified is strong.

4.2 There appear to be some general patterns that can be identified. Much research has focused on methods for re-vegetation of bare peat, with either vascular plants, aimed at stabilizing eroding peat surfaces, or with *Sphagnum*, and these have largely provided evidence of different degrees of success, with those resulting in failure normally involving lowland agricultural grasses. The long-term effects of such interventions are poorly understood. Establishing vascular plant-dominated vegetation on blanket peat is unlikely to result in restoration of the functions of an intact bog; however it will slow the rate of the loss of peat, but will not prevent or reverse it.

4.3 The impact of different semi-natural vegetation types, which respond to different land management efforts, seems to be strong on many peatland functions, impacting on erosion, hydrology, gas flux, biodiversity, and loss of dissolved and particulate carbon. Many of the studies contrast the properties of blanket peatland dominated by *Sphagnum*, *Eriophroum* (usually *vaginatum*) and *Calluna vulgaris*. For most functions of peatlands, it would seem that *Sphagnum* is better than *Eriophorum* and both are better than *Calluna vulgaris*. As yet, no research has been published on how best to control the dominance of *Calluna* on blanket peatland, there has been however considerable effort made to promote *Calluna* establishment, not only on bare peat but also in existing semi-natural vegetation.

4.4 *Molinia caerulea* is also a focus of investigation, particularly its eradication, whereas there is little known of its impact on peatland function. The evidence presented on peat-forming plants raises the possibility that *Molinia* has long been a common plant on some of our blanket peatlands and may have formed considerable amounts of peat, hence locking up carbon. *Molinia*, as a deciduous grass, therefore is generally unpopular with farmers, and as a vigorous dominant, also unpopular with conservationists. However, its impact on carbon sequestration or water quality is little understood, further exploration may cause us to question the demonization of this species.

4.5 Much research effort has considered the impacts of drainage, and even more consideration has been given to drain blocking. Localised effects on vegetation and hydrology have been demonstrated, but strong consistent patterns in hydrology or water quality are not evident. It would appear other factors confound these interpretations and a more holistic approach to understanding the place of drainage and blocking among other blanket peatland managements would help to identify the true controls on water movement and quality, and identify where we can manage this to improve ecosystem services.

4.6 Studies of eroded and hagged peatlands, especially those that may not be totally bare, have not featured strongly in this topic review, but are likely to have hydrological and other impacts at least as important as drainage. Bare peat seems to attract a strong focus, with many studies exploring techniques for its re-vegetation. However, some studies seem to show that revegetating bare peat, while stopping it from washing away, may encourage more active microbes. These microbes may accelerate the loss of peat, although likely to be on a smaller scale than the erosional losses avoided by re-vegetation.

4.7 No evidence was found for a full restoration of a degraded blanket peatland to a peat-forming community rich in *Sphagnum* mosses. This is the desired end point of blanket bog restoration for most conservationists, but cannot deliver unequivocal benefits across all functions. However, the evidence in this topic review would largely suggest that the resulting balance of hydrological, geochemical, biodiversity and other benefits would certainly outweigh the alternatives.

5 Conclusions

5.1 This topic review set out to answer a number of targeted questions pertinent to restoration of blanket peatlands. The conclusions for each of the questions follow:

What are the hydrological, structural and floristic characteristics indicative of functioning and active blanket bog?

5.2 This topic review shows that blanket bogs, when supporting a balanced range of *Sphagnum* mosses, cotton grasses, dwarf shrubs, sedges and other typical wetland plants, are characterised by a high water table that fluctuates in a surface zone. These systems form peat by adding material into their waterlogged lower layers, which accumulate due to their high retention, and slow movement of rainwater. New rain falling travels mainly across the bog surface, slowed by bog mosses and cotton grasses, but can also enter peat pipes that weave through the peat mass and underlying substrate. Decomposition is slow, with peat carbon being released as methane, and little being lost as dissolved organic carbon.

What species of plant are peat- forming and what are their physical (hydrological and other) requirements?

5.3 Most peat formed is by *Sphagnum* mosses, with *Sphagnum* '*imbricatum'* (now split into *S. affine* and *S. austinii*) often being the most important species, but with *Sphagnum papillosum* and others also occasionally important. Cotton grasses, usually *Eriophorum vaginatum*, can also predominate, but much peat is often amorphous organic matter, or unidentifiable monocotyledonous material. Much of this may be *Molinia caerulea*, which also appears to form peat, recognisable at the surface, and occasionally also lower down the profile. Dwarf shrubs, including *Calluna*, feature throughout most peat profiles, but are never dominant except in the litter layers at the surface. The peat-forming plants listed above require high water tables, which not only enables them to out-compete plants of drier habitats, but also is a requirement for the preservation of the peat material they deposit. Bogs are, by definition, ombrotrophic, acidic and require low nutrient conditions for these species to thrive.

What factors (management, atmospheric deposition and climatic) affect the hydrological, structural and floristic status and composition of blanket bog, and leads to its degradation?

5.4 This topic review has found evidence of loss of peatland function as a result of afforestation, peat cutting, drainage, accelerated erosion and atmospheric deposition of pollutants. These result in a loss of typical blanket bog plants, often becoming more dominated by those blanket bog species that are better adapted to drier habitats. This can result in higher bulk densities, shrinking and subsidence of the peat, but also more water flow through larger pores, which enlarge to form more peat pipes. The impact of drainage may be limited in its extent to narrow areas around ditches, but these ditches can erode on steeper slopes, and may have a more widespread effect in low rainfall areas. Where the peat is drier, peat accumulation ceases, and while there is a reduction in methane emissions, and there seems to be little additional loss of carbon as CO_2, much dissolved carbon is lost, discolouring water and reducing the peat's carbon store. Where peat is bare, it can erode rapidly, and lose particles of peat into streams.

What interventions are required to restore a degraded blanket bog to a functioning and active blanket bog system with abundant peat-forming species, and over what timescale?

5.5 The evidence suggests that many different steps may be required to restore the functions of an intact bog to a degraded blanket peatland. Afforested peatlands can begin the process of restoration by felling the trees. Felling, in younger plantations can rapidly restore the blanket bog vegetation, even where trees are felled to waste and left on site. Bare eroding peat can be stabilised by re-vegetation, often aided by amelioration of growth conditions with lime, fertiliser, stabilisation techniques and careful selection of seeds. While heather and grasses can prevent particulate loss, they will not form peat, and ongoing loss of dissolved peat carbon may continue. Where the vegetation has become dominated by *Molinia* this can be controlled, but intensive interventions are required and the impact on wider functions, of *Molinia* or its control, are unknown. The key to blanket bog formation, and also to its restoration, is to re-establish abundant *Sphagnum* mosses, and this has been successfully demonstrated on cut over raised bog peatlands where management of water table, peat conditions, surface humidity, source and type of moss material and use of mulches can all help to increase success. The conditions found on bare and eroding blanket peatland are more challenging. Attempts to reintroduce *Sphagnum* to upland blanket bogs are comparatively recent, and as yet levels of persistence are unknown. No studies considered in this topic review demonstrate full recovery of blanket bog and its functions, and therefore the timescale for a full recovery remains unknown.

Does the blocking of artificial drainage channels (grips) on degraded blanket bog result in a functioning and active blanket bog with abundant peat forming species and representative bog flora and fauna. If so, do all drains require to be blocked?

5.6 There is some weak evidence that blocking of grips through blanket bogs provides some restoration of blanket bog vegetation. It usually raises the water table, increases river base flow in droughts, and improves conditions for invertebrates, including those important as food for moorland birds. Grip blocking may reduce export of POC, DOC, and reduce flashy flows that can cause flooding, but this seems highly variable between locations. It does however, seem to reverse the impact of drainage on surface peat properties, possibly increasing hydraulic conductivity and reducing density. Using peat dams appears to be the most effective, and cost-effective, approach, but the raised water tables will increase methane emissions. The topic review suggests that grips on gentler slopes (under 2^{o}) will probably re-vegetate without intervention, and so may not be a priority for blocking. They may still however influence the hydrology of the surrounding peat area.

Are there conditions where it is not feasible to completely restore a degraded blanket bog to a fully functioning bog system with its representative flora and fauna, and if so what is likely to prevent their full recovery.

5.7 This topic review has found no examples of unrestorable bogs, where conditions for growth and recovery of bog species are either not prohibitive or amenable to management. However, social, cultural, political, economic or other considerations may mean that peatland restoration is not viable.

Are there any wider environmental impacts resulting from the restoration of degraded blanket bogs?

5.8 This topic review has identified a wide range of predominantly hydrological and geochemical environmental functions that are affected both by degradation and restoration of peatlands. The impact of degradation seems, overall, to be more certain than that of restoration. This may be partly due to timescale, since degradation has been ongoing for longer, and recovery of intact peatland functions will require, above all else, time.

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7 Glossary and acronyms

Term	
block-cut	Subject to peat extraction by draining, cutting trenches and removing peat from the vertical peat face.
bog	ombrogenous mire
bulk density	Also known as dry bulk density. The mass of dry material per unit volume.
catchment	The area upslope of a point, line or area, towards which all surface water drains (for example, the catchment of the grip) OR an area where all the surface water drains towards a common point. Often the same thing.
CH_4	Methane
CO_2	Carbon dioxide
conductivity (1)	Hydrological conductivity = a measure of the inherent properties of a material that control how quickly water will move through them.
conductivity (2)	Electrical conductivity, used in testing solutions (soil water, streams etc.) to indicate the concentration of a range of solutes, interacting with other chemical properties.
cut-over	Subject to peat extraction, more usually by mechanised milling or vacuum-harvesting of peat.
DOC	Dissolved Organic Carbon
efficiency	(hydrology, of catchments) the proportion of rainfall entering a catchment during a given period, which leaves the catchment as stream water. ie. more 'efficient' catchments will export more of their rainfall than inefficient ones.
fen	Mire receiving water from sources other than precipitation.
flashiness	The extent to which a flow of water is flashy.
flashy	of hydrographs during rainfall events. Responding quickly by increases in flow to the onset in the catchment of rainfall, maximum rain deposition, and by decreases in flow to cessation or reduction in rainfall intensity.
GHG	Greenhouse gas (CO_2, N_2O, CH_4)
GPR	Ground Penetrating Radat
ground water	Water held in the bedrock, drift and soils forming a continuous mass in one or all of these.
hydrograph	A record showing the flow rate (volume/time) of a stream or channel at a given point, over time.
mire	Habitat which forms peat
N_2O	Nitrous oxide
NEE	Net Ecosystem Exchange (of CO_2)

Table continued…

Term	
ombrogenous	Formed due to the influence of precipitation.
ombrotrophic	(of a habitat or ecosystem) receiving all its nutrient supply from precipitation or atmospheric deposition.
PAR	Photosynthetically active radiation.
peat	(i) the partially decomposed remains of plants and other organisms which have accumulated in waterlogged conditions, at the surface of the soil profile or as material infilling water bodies. Also (ii) a soil texture class encompassing any soil material with greater than 20-30% organic matter (depending on clay content).
pH	A measure of the acidity or alkalinity of a solution or material.
POC	Particulate Organic Carbon
Sphagnum	A genus of mosses characterised by whorled branched growth form, also called 'bog mosses'.
water table	The distance of a waterlogged zone beneath the surface. Note that in many bogs this water table is not the ground water, in that it is discontinuous with a more freely drained zoned at its base. However, in raised bogs, water table in bogs may be continuous with ground water, but largely not interacting, because the water table is raised bog the gravitational level of the ground water due to low hydrological conductivity of peat.
yield	(hydrology) the total amount of water exiting a catchment.
SCP	Spheroidal Carbonaceous Particles – soot particles found in peat deposits associated with industrial activity
gully	A channel caused by erosion of a peat mass, which may be branched or linear, and may be found entirely within the peat mass, or cutting through into underlying mineral material (also gullying, gullied).
anastomosing	Splitting and rejoining a.k.a. reticulate.
reticulate	Forming a net a.k.a. anastomosing.
hagg	A remnant block of undisturbed peat that has been separated from the rest of the peat mass by anastomosing gullies.
macrofossil	Literally large fossils, used in peat stratigraphy, however, to denote recognisable plant remains, usually requiring microscopy.
BAP	Biodiversity Action Plan

8 Scientific names and synonyms

Currently valid scientific names are given in bold:

Sphagnum angustifolium =

Sphagnum papillosum =

Sphagnum fuscum =

Sphagnum capillifolium =

Sphagnum imbricatum = ***Sphagnum affine***

Sphagnum recurvum = probably ***Sphagnum fallax***

Trichophorum cespitosum = *Trichophorum cespitosum* subsp. *germanicum* (Palla) Hegi

Calluna = *Calluna vulgaris* (L.) Hull

Molinia = *Molinia caerulea* (L.) Moench

Appendix 1 List of references following initial screening process

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Appendix 4 Study categorization

The distribution of broad study type by the categories given in Table 2 and by the quality categories given in Table 3 is provided below in Table B.

Table A Categorisation of studies

Study type and quality	Authors and date
1++	(Anderson *et al*, 1995); (Anderson *et al*, 2000); (Boudreau & Rochefort, 1998); (Bussell *et al*, 2010); (Buttler *et al*, 1998); (Campeau & Rochefort, 1996); (Chirino *et al*, 2006); (Groeneveld *et al*, 2007); (Grosvernier *et al*, 1995); (Grosvernier *et al*, 1997); (Milligan *et al*, 2003); (Rochefort & Campeau, 2002); (Rochefort *et al*, 2003); (Sheridan, 2008); (Todd *et al*, 2000); (Marrs *et al*, 2004)
1+	(Bugnon *et al*, 1997); (Caporn *et al*, 2007); (Ferguson, Lee & Bell, 1978); (Milligan *et al*, 1999); (Milligan *et al*, 2004); (Robroek *et al*, 2009 [1+]); (Richards *et al*, 1995); (Skeffington *et al*, 1997)
1-	(Rochefort *et al*, 1995)
2++	(Carroll *et al*, 2009); (Evans *et al*, 2005); (Grayson & Holden, 2012a); (Grayson & Holden, 2012b); (Green *et al*, 2011); (Gunnarsson *et al*, 2008); (Holden *et al*, 2001); (Holden *et al*, 2008); (Holden *et al*, 2011); (Holden *et al*, 2012); (Holden, 2006); (O'Reilly, 2008); (Ramchunder *et al*, 2012); (Sheppard *et al*, 2011); (Shotbolt *et al*, 1998); (Stewart and Lance,1991); (Wilson *et al*, 2010); (Wilson *et al*, 2011); (Wilson *et al*, 2011b); (Worrall *et al*, 2011)
2+	(Armstrong *et al*, 2010); (Clay *et al*, 2009); (Clymo & Reddaway, 1971); (Farrick & Price, 2009); (Fenner *et al*, 2011); (Gibson *et al*, 2009); (Glendinning, 2012); (Hajek, 2009); (Holden *et al*, 2006); (Holden *et al*, 2007); (Holden, 2005b); (Holden, 2009a); (Komulainen *et al*, 1999a); (Malmer & Wallen, 1999); (McHugh *et al*, 2000); (Phillips *et al*, 1981); (Robinson, 1985); (Ross, 2011); (Wallage & Holden, 2011); (Wallage *et al*, 2006); (Warburton, 2003); (Worrall *et al*, 2010)
2-	(Anderson *et al*, 1995b); (Anderson *et al*, 2011a); (Anderson *et al*, 2011b); (Armstrong *et al*, 2008); (Buckler, 2007); (Caporn *et al*, 2006); (Gore & Godfrey, 1981); (Hinde *et al*, 2010); (Phillips, 2008); (Tallis & Yalden, 1983)
3+	(Burke, 1975); (Chambers *et al*, 2007a); (Chambers *et al*, 2007b); (Jonczyk *et al*, 2009); (Holden & Burt, 2002); (Malmer *et al*, 1994); (Robroek *et al*, 2010)
3-	(Ardron, 1999); (Burtt & Hawke, 2008); (Mackay & Tallis, 1996); (Murphy, 2008)
4	(Lindsay, 1995); (Lindsay *et al*, 2003)

The scientific approach to the 105 studies included in the review comprised:

- 31 treatment/control comparisons;
- 13 monitoring / repeat survey;
- 15 surveys;
- 12 case studies;
- 8 before and after studies;
- 6 treatment comparisons;
- 4 surveys with control/treatment comparisons;
- 4 treatment/control comparisons with controlled before and after studies;
- 6 reviews;
- 1 systematic review of treatment/control comparison studies;

- 1 survey, with a case study and a before and after study;
- 1 monitoring with a treatment/control comparison;
- 1 meta-analysis;
- 1 controlled before and after study with a case study; and
- 1 controlled before and after study.

Table B presents the studies by country and lead author.

Table B Summary of studies by country of origin

Country of origin	Number of studies	Authors
UK	78	(Anderson *et al*, 1995); Anderson *et al*, 2000); (Ardron, 1999); (Burtt & Hawke, 2008); (Gibson *et al*, 2009); (Holden, 2005b); (Holden, 2006); (Holden *et al*, 2006); (Mackay & Tallis, 1996); (Phillips *et al*, 1981); (Anderson *et al*, 1995b); (Anderson *et al*, 2011a); (Anderson *et al*, 2011b); (Buckler, 2007); (Caporn *et al*, 2007); (Chambers *et al*, 2007a); (Chambers *et al*, 2007b); (Clay *et al*, 2009); (Evans *et al*, 2005); (Gore & Godfrey, 1981); (Hinde *et al*, 2010); (Holden *et al*, 2007); (Marrs *et al*, 2004); (Milligan *et al*, 2004); (Milligan *et al*, 1999); (Milligan *et al*, 2003); (Richards *et al*, 1995); (Ross, 2011); (Sheridan, 2008); (Skeffington *et al*, 1997); (Tallis & Yalden, 1983); (Todd *et al*, 2000); (Armstrong *et al*, 2008); (Glendinning, 2012); (Grayson & Holden, 2012a); (Grayson & Holden, 2012b); (Holden *et al*, 2011); (Jonczyk *et al*, 2009); (Phillips, 2008); (Ramchunder *et al*, 2012); (Wallage & Holden, 2011); (Wilson *et al*, 2010); (Wilson *et al*, 2011); (Green *et al*, 2011); (Armstrong *et al*, 2010); (Fenner *et al*, 2011); (Wallage *et al*, 2006); (Wilson *et al*, 2011b); (Worrall *et al*, 2011); (Holden, 2009a); (Holden & Burt, 2002); (Holden *et al*, 2001); (Holden *et al*, 2008); (Holden *et al*, 2012); (Lindsay, 1995); (Caporn *et al*, 2006); (Carroll *et al*, 2009); (Clymo & Reddaway, 1971); (Lindsay *et al*, 2003); (O'Reilly, 2008); (Robinson, 1985); (Robroek *et al*, 2010); (Shotbolt *et al*, 1998); (Stewart and Lance,1991); (McHugh *et al*, 2000); (Warburton, 2003); (Sheppard *et al*, 2011); (Ferguson, Lee & Bell, 1978); (Coulson *et al*, 1990 [2++]); (Holden, 2005a [2++]); (Armstrong *et al*, 2009 [2+]); (Bridges, 1985 [2++]); (Tallis, 1998 [4]); (Bellamy *et al*, 2012 [2+]); (Carroll *et al*, 2011 [2++]); (Lindsay, 1995 [4]); (Wishart and Warburton, 2001 [3-]); (Stroud *et al,* 1988 [4])
Canada	11	(Boudreau & Rochefort, 1998); (Bugnon *et al*, 1997); (Campeau & Rochefort, 1996); (Chirino *et al*, 2006); (Farrick & Price, 2009); (Groeneveld *et al*, 2007); (Rochefort & Campeau, 2002); (Rochefort *et al*, 1995); (Rochefort *et al*, 2003); (Ferland & Rochefort, 1997 [1++]); (Lavoie *et al*, 2005 [2+])
Finland, Estonia	4	(Komulainen *et al*, 1999a); (Robroek *et al*, 2009 [1+]); (Tuittila *et al*, 2003 [2+]); (Vasander *et al*, 2003 [2-])
Ireland	3	(Burke, 1975); (Murphy, 2008); (Robroek *et al*, 2009 [1+])
Switzerland	3	(Buttler *et al*, 1998); (Grosvernier *et al*, 1997); (Grosvernier *et al*, 1995)
Various worldwide	3	(Bussell *et al*, 2010); (Worrall *et al*, 2010); (Malmer *et al*, 1994)
Sweden	2	(Gunnarsson *et al*, 2008); (Malmer & Wallen, 1999)
Czech Republic, Germany	2	(Hajek, 2009); (Sliva & Pfadenhauer, 1999 [1++])

A total of 16 studies measured short-term outcomes (up to 12 months follow up) only ((Holden, 2005b); (Bugnon *et al*, 1997); (Buttler *et al*, 1998); (Campeau & Rochefort, 1996); (Caporn *et al*, 2007); (Evans *et al*, 2005); (Farrick & Price, 2009); (Grosvernier *et al*, 1997); (Grosvernier *et al*, 1995); (Rochefort & Campeau, 2002); (Ramchunder *et al*, 2012); (Wilson *et al*, 2010); (Wilson *et al*, 2011); (Green *et al*, 2011); (Wallage *et al*, 2006); (Ferguson, Lee & Bell, 1978).

A total of 66 studies measured long-term outcomes (over 12 months follow up) only ((Anderson *et al*, 1995); Anderson *et al*, 2000); (Ardron, 1999); (Burke, 1975); (Clay *et al*, 2009) ; (Gibson *et al*, 2009); (Holden *et al*, 2006); (Mackay & Tallis, 1996); (Phillips *et al*, 1981); (Anderson *et al*, 2011a); (Anderson *et al*, 2011b); (Boudreau & Rochefort, 1998); (Buckler, 2007); (Chirino *et al*, 2006); (Murphy, 2008); (Gore & Godfrey, 1981); (Groeneveld *et al*, 2007); (Hinde *et al*, 2010); (Holden *et al*, 2007); (Komulainen *et al*, 1999a); (Marrs *et al*, 2004); (Milligan *et al*, 2004); (Milligan *et al*, 1999); (Milligan *et al*, 2003); (Richards *et al*, 1995); (Rochefort *et al*, 1995); (Rochefort *et al*, 2003); (Ross, 2011); (Sheridan, 2008); (Skeffington *et al*, 1997); (Tallis & Yalden, 1983); (Todd *et al*, 2000); (Armstrong *et al*, 2008); (Glendinning, 2012); (Grayson & Holden, 2012a); (Grayson & Holden, 2012b); (Holden *et al*, 2011); (Jonczyk *et al*, 2009); (Wallage & Holden, 2011); (Armstrong *et al*, 2010); (Fenner *et al*, 2011); (Wilson *et al*, 2011b); (Worrall *et al*, 2011); (Holden, 2009a); (Holden & Burt, 2002); (Holden *et al*, 2001); (Holden *et al*, 2008); (Holden *et al*, 2012); (Lindsay, 1995); (Caporn *et al*, 2006); (Carroll *et al*, 2009); (Clymo & Reddaway, 1971); (Hajek, 2009); (Lindsay *et al*, 2003); (Malmer *et al*, 1994); (Malmer & Wallen, 1999); (Robroek *et al*, 2009 [1+]); (Robinson, 1985); (Shotbolt *et al*, 1998); (McHugh *et al*, 2000); (Warburton, 2003); (Sheppard *et al*, 2011)) (Bridges, 1985 [2++]); (Sliva & Pfadenhauer, 1999 [1++]); (Tuittila *et al*, 2003 [2+]); (Vasander *et al*, 2003 [2-]).

A single study measured a combination of short and long-term measures (Anderson *et al*, 1995b) and a for a further 10 studies an assessment of the length of outcome measures was either not possible or inappropriate to the study type ((Burtt & Hawke, 2008); (Gunnarsson *et al*, 2008); (Holden, 2006); (Chambers *et al*, 2007a); (Chambers *et al*, 2007b); (Bussell *et al*, 2010); (Worrall *et al*, 2010); (O'Reilly, 2008); (Robroek *et al*, 2010); (Stewart and Lance,1991)).

Appendix 5 Analysis of evidence

This report presents each of the questions addressed by this review, sub-divided into topics, and presents evidence that has been identified from the studies reviewed that is relevant to these topics. The range of evidence presented is then summarized into one or more Evidence statements, which have been presented in the main body of the report. Some sections also provide an analysis of areas where evidence appears to be weak or lacking, as potential priorities for additional research or further review.

What are the features of a bog in good condition?

This section identifies evidence considered in this review that addresses the following key question.

Key question: a) what are the hydrological, structural and floristic characteristics indicative of functioning and active blanket bog?

The definition of a bog in good condition, and to some extent its structural characteristics have already been provided in paragraph 1.26. This part of the topic review, therefore, seeks to illustrate the likely characteristics in terms of the hydrological function of an intact bog, along with other functional characteristics that are influenced by hydrology.

See also paragraph 2.5 (Shotbolt *et al*, 1998 [2++]) for data on bulk density, water content and surface subsidence/rise dynamics in intact peatlands, as well as possible evidence of mass movement.

Water tables in intact bogs

One study (Holden *et al*, 2006 [2+]) comparing two drained with two undrained blanket peat catchments in the North Pennines found mean water tables were higher and more uniform (0-12cm) in the intact peatlands than in drained peatlands.

A case study of peat composition and accumulation in the Forest of Bowland observed that water tables were higher in the *Sphagnum*-dominated area (mean 8.4 cm), than in the gullyside *Eriophorum* area (mean 25.1) or the hagg-top dwarf shrub area where water tables were too low to be measured for most of the year (39-55 cm).

A report on the impacts of deforestation on Irish bogs (Murphy, 2008 [3-]) reported that water tables in intact blanket bogs were generally within 5 cm of the mire surface except in dry weather, but drained bogs had water tables more than 30 cm below the surface, and lower in dry weather.

A case study comparison of drained, blocked and intact peatlands in Upper Wharfefale (Holden *et al*, 2011 [2++]) found that mean water table depths were significantly different between the intact, blocked and drained sites being 5.8, 8.9 and 11.5 cm from the surface, respectively.

A comparative survey of 3 catchments (intact, drained and blocked peatlands (Wallage & Holden, 2011 [2+]) found that mean water table in the intact peatland was highest (5.8 cm from the surface) and remained at the surface for longest (18% of time), compared with 10.1 cm in the drained area and 7.3 cm in blocked area which had water tables at the surface for only 2% of the time.

A comparative survey and detailed case study of drained and intact blanket peat catchments in the North Pennines (Stewart and Lance, 1991 [2++]) found that water tables in intact peatlands, and those furthest from drainage grips in drained peatlands, were higher and less responsive to rainfall events than those near drainage channels.

A case study on the impacts of drainage in a hyper-oceanic blanket bog dominated by Shoenus nigricans (Burke, 1975 [3+]) found that water levels in the dipwells in the drained plot were always lower than in the undrained plots.

Evidence statement

The following statement is supported by the evidence above:

- Functioning and active blanket bogs are characterised by a high mean annual water table (5-10 cm from surface). (Holden *et al*, 2006 [2+]); (Holden *et al*, 2011 [2++]); (Wallage & Holden, 2011 [2+]); (Stewart and Lance, 1991 [2++]); (Burke, 1975 [3+]) supported by (Mackay & Tallis, 1996 [3-]); (Murphy, 2008 [3-]). There are no studies that refute it.

Structure of intact blanket bogs

A review of the structure, biology and chemistry of bogs (Lindsay, 1995 [4]) reported that bog formation is typically driven by presence of *Sphagnum*, which produces litter that is chemically resistant to decay and which generates peat that has a slow rate of downward water movement.

A descriptive review of the formation and structure of bogs ((Lindsay *et al*, 2003 [4]) describes a permanently waterlogged and anaerobic zone, the catotelm, lying close to the bog surface, with a thin acrotelm of seasonally fluctuating water levels in which the mosses and vascular plants grow.

A comparative survey of three blanket peat catchments in Yorkshire (Wallage & Holden, 2011 [2+]) found that intact blanket bogs had significantly higher near-surface macropore flows than the drained or blocked areas.

A field survey of macroporosity under different semi-natural vegetation and bare peat at Moor House, North Pennines (Holden *et al*, 2001 [2++]), found that *Sphagnum*-dominated blanket peat macropore flow rates that changed little between 0 and 20 cm, compared with those under *Calluna* or *Eriophorum*-dominated vegetation, where macropore flow declined rapidly over the same depth, indicating greater macropore, and overall, water flow in near-surface peat under *Sphagnum*.

A comparative case study of drained and undrained sites in Upper Wharfedale, Yorkshire (Holden *et al*, 2011 [2++]), found that intact peatlands showed smaller fluctuations during storm events compared with drained peatland, and rate of decline following the storm event was slower.

Evidence statement

The description of bog structure is not a subject that is amenable to intervention-based experimental research, however the statements above suggest that in intact bogs there is a surface layer of high hydraulic conductivity, but that this is underlain by a high water table layer (where water does not drain due to low hydraulic conductivity) which results in attenuated water table fluctuations following rainfall. The following statement is therefore supported by the evidence above:

- Active blanket bogs are characterised by a zone of fluctuating water table, with high hydraulic conductivity, overlying a thicker zone of peat with almost permanent waterlogging and low hydraulic conductivity (the catotelm). (Lindsay, 1995 [4]); (Lindsay *et al*, 2003 [4]); (Wallage & Holden, 2011 [2+]); (Holden *et al*, 2001 [2++]); (Holden *et al*, 2011 [2++]). There are no studies that refute it.

Peat accumulation in intact blanket bogs

A field study examining rates of short term peat accumulation in a Swedish bog using measurements around pine seedlings (Gunnarsson *et al*, 2008 [2++]) found that peat growth rate was significantly and positively correlated with *Sphagnum* cover and modelled peat decay rates were lowest in the more *Sphagnum*-rich vegetation.

A study of peat macrofossils in eroded and intact blanket peat in the Forest of Bowland (Mackay & Tallis, 1996 [3-]) found that lower peat horizons were dominated by macrofossils of *Eriophorum vaginatum* and upper layers dominated by *Sphagnum* papillosum, with subcomponents of ericaceous shrubs and other *Sphagnum* species.

A review of mire and bog processes in the northern hemisphere (Malmer *et al*, 1994 [3+]) reported that *Sphagnum* has formed the majority of blanket bog peat and that high water table and anoxic conditions are required to prevent oxidative decomposition of organic remains.

A case study of peat macrofossils and palynology at several blanket peat and shallower peaty soil locations in South Wales (Chambers *et al*, 2007b [3+]) found that unidentified monocotyledons, *Sphagnum* and ericaceous plants were important at profile bases, becoming dominated more by *Sphagnum affine (imbricatum)* higher in the profile, and by varying amounts of *Eriophroum vaginatum* and *Molinia*.

Evidence statement

The evidence for peat accumulation is hard to demonstrate experimentally due to the long timescales involved. However since 'active' peatlands are those that deposit peat, the macrofossil remains that make up peat deposits are indicators of the types of habitats that have accumulated peat in the past. Patterns of peat accumulation and carbon accumulation are the same, since carbon forms approximately half of dry blanket peat material (Lindsay, 2010). The following statement is supported by the evidence above:

- Functioning and active peatlands accumulate peat, and peat carbon, through ongoing deposition of material into the catotelm. (Gunnarsson *et al*, 2008 [2++]); (Malmer *et al*, 1994 [3+]); (Chambers *et al*, 2007b [3+]) supported by (Mackay & Tallis, 1996 [3-]). There are no studies that refute it.

Peat pipes and gullies in intact peatlands

A field survey of 320 sites across upland Britain (Holden, 2006 [2++]) determined that undrained peatlands were likely to have 41.6km of peat pipes per square kilometre, and that this modelled value was close to observed values.

A case study of intact peatland at Moor House, North Pennines, (Holden & Burt, 2002 [3+]), mapped peat pipes in this relatively intact peatland. Pipes appeared to have little impact on drainage of the catotelm, with some pipes not carrying water despite high water tables, but instead seemed to collect runoff and near surface flow.

A repeated monitoring survey of peat pipes at Moor House (Holden *et al*, 2012 [2++]) found that these were present, and could appear, infill, collapse, or enlarge over a ~2.5 year period.

A review of blanket bog distribution and the timing and conditions for its formation (Tallis, 1998 [4]) concluded that gullying of blanket peat is a natural process, but can be initiated by both long-term management practices and by climate change. It also concluded that the presence of gullies need not stop peat growth and suggests that some gullies should be conserved as natural examples of peatland geomorphology.

Evidence statement

The following statement is supported by the evidence above:

- Peat pipes occur naturally in relatively intact peatlands. (Holden, 2006 [2++]); (Holden & Burt, 2002 [3+]); (Holden *et al*, 2012 [2++]). A further review study suggests that gullies are natural features of undamaged peatlands (Tallis, 1998 [4]). There are no studies that refute these statements.

Runoff and hydrology in intact peatlands

A comparison of drained and undrained catchments in the North Pennines (Holden *et al*, 2006 [2+]) found that overland flow was far more common in the intact sites than in drained sites and that intact catchments had lower hydrograph peaks, and significantly longer lag times, than the drained catchments.

A comparison of the data from two drained and two undrained catchments in the North Pennines (Robinson, 1985 [2+]) which seem likely to be the same catchments as studied by (Holden *et al*, 2006 [2+]) found that the two intact catchments had flood hydrographs that suggested a significantly longer mean response time to peak flow (less flashy flow) than the catchments with artificial drainage, based on data from all non-snow storm events in the four catchments over two years.

A study of moorland footpaths, compared to undisturbed blanket bog vegetation (Robroek *et al*, 2010 [3+]) found that runoff occurred 5.5-7.4 times more often on paths than in the intact vegetation.

A survey of runoff velocities relating to moorland vegetation observed that runoff events were common in the study area of intact blanket peatland, dominated by *Eriophorum* spp. and *Sphagnum* spp. (Holden *et al*, 2008 [2++]).

Evidence statement

The following statement is supported by the evidence above:

- Functional and active blanket bogs generate predominantly surface and near-surface runoff and so are characterised by rapid flow responses compared to most other areas, but because the channel network is limited these do not necessarily give rise to such rapidly-responding (flashy) hydrographs compared to less intact peatlands. (Holden *et al*, 2006 [2+]); (Robinson, 1985 [2+]); (Robroek *et al*, 2010 [3+]); (Holden *et al*, 2008 [2++]).

Impact of intact bog vegetation on runoff

A comparison of artificially induced runoff speed across different moorland vegetation types in the North Pennines (Holden *et al*, 2008 [2++]) found that overland flow was consistently and significantly higher over bare peat than over vegetated surfaces, and flow over *Sphagnum*-dominated vegetation was significantly lower than for other vegetation types.

Evidence statement

The following statement is supported by the evidence above:

- Runoff travels more slowly across *Sphagnum*-dominated vegetation, than some other moorland vegetation types or bare peat. (Holden *et al*, 2008 [2++]). There are no studies that refute it.

Dissolved Organic Carbon and water colour in intact peatlands

A study examining the impact of grip blocking, with comparison to drained and untrained catchments across four sites in the Pennines (Gibson *et al*, 2009 [2+]) found that intact sites had significantly lower absorbance and DOC concentrations than drained sites and that, when water yield was considered as a covariate, undrained catchments had significantly lower DOC export than drained and drain-blocked catchments.

A comparison of the carbon budgets of bare, vegetated and re-vegetated peatlands in the Peak District (Worrall *et al*, 2011 [2++]) found that lowest DOC flux was from the *Eriophorum*-dominated site (13 tonnes C km^{-2} yr^{-1}), and highest DOC flux was from the dwarf shrub dominated site with managed burning (96 tonnes C km^{-2} yr^{-1}), while DOC flux from bare peat and re-vegetated sites varied between these extremes.

Evidence statement

The following statement is supported by the evidence above:

- Intact (undrained) blanket peatlands export less DOC and water colour than drained or drain-blocked peatlands. (Gibson *et al*, 2009 [2+]); (Worrall *et al*, 2011 [2++]). There are no studies that refute it.

Methane emissions from intact peatlands

A systematic review of the impact of drainage and re-wetting of peatlands on greenhouse gas and carbon flux (Bussell *et al*, 2010 [1++]) found that 27 studies compared methane in drained and intact peatlands, and intact peatlands emitted significantly more CH_4 (by ~8mg CH_4 m^{-2} day^{-1}) than drained peatlands.

However, a further field study in the Peak District examining the greenhouse gas and carbon budgets of intact, bare and re-vegetated peatlands found no significant differences in methane emissions between intact peatland, bare peatlands, dwarf-shrub covered peatlands or re-vegetated peatlands (Worrall *et al*, 2011 [2++]).

Evidence statement

The following statement is supported by the evidence above:

- Intact peatlands are net emitters of methane, and emit more than drained peatlands and less than recently restored peatlands. A single study, representing data from 27 quality-assessed studies, supports this statement: (Bussell *et al*, 2010 [1++]). There was one study that could find no difference in methane flux between intact and damaged peatlands (Worrall *et al*, 2011 [2++]).

Areas requiring further study

The contention that intact peatlands have 'flashy' storm hydrographs is not supported by the evidence in this review. Although intact peatlands may have more of their rainfall leaving catchments as overland flow than damaged peatlands, the speed at which this travels across the surface and through the upper layers of an intact peatland may slow the flow and reduce flashy flow. However, the evidence for this has come from only 2 catchment scale studies, both of which are likely to have been conducted on the same study catchments. It cannot be ruled out that local differences in topography have influenced these results. Furthermore, the comparators in this review are between intact and damaged peatlands, and intact peatlands may indeed have flashier storm hydrographs than non-peat catchments with smaller areas of waterlogged soils.

A study of afforestation impacts on peat subsidence using transects of peat properties crossing intact and afforested bogs (Shotbolt *et al*, 1998 [2++]) seems to indicate that over decades there have been reductions in surface height in the highest, wettest, least dense intact peat, and increases in height where peat is driest and densest and downslope (where there is a layer of less dense, wetter peat underlying this area). One potential interpretation of this is that gradual mass movement has occurred, with accumulation of wet peat material upslope which is gradually sliding under the peat downslope, raising it and allowing it to dry and become denser. Gradual mass movement of peat, despite this material being ~95% water, is not well studied, but may help to explain the dynamics of peat distribution and erosion on hill top peat. More research is required to demonstrate the occurrence of gradual peat mass movement and investigate its implications for erosion, degradation and restorability.

Peat-forming plants

This section identifies evidence considered in this review that addresses the following key question.

Key question: c) what species of plant are peat- forming and what are their physical (hydrological and other) requirements?

It has already been noted in this review that peat formation is more a characteristic of the prevailing environmental conditions, rather than necessarily the type of plant species that contribute litter. However, a certain range of plant species are associated with the ombrogenous, and permanently waterlogged conditions that are required to form blanket peat. Furthermore, the properties of the litter of plants, mainly in terms of its hydraulic conductivity, serve to retain water and encourage waterlogged conditions. This section seeks to present evidence on the niche requirements of key blanket bog species, and on the types of plants that have demonstrably formed peat in the past, through analysis of their remains in peat deposits, or which can be demonstrated to be forming peat in current studies.

Wetland plants, waterlogging and peat formation

A review of peat formation and mire processes in the northern hemisphere (Malmer *et al*, 1994 [3+]) noted that while *Sphagnum* is not essential to peat formation , historically *Sphagnum* has formed the bulk of most blanket bog peat and that high water table and anoxic conditions are required to prevent oxidative decomposition of organic remains.

A field experiment examining impact of clipping existing vegetation , and mulches, on *Sphagnum* re-establishment in a cut-over raised bog peatland in Canada (Boudreau & Rochefort, 1998 [1++]) found that *Sphagnum* establishment was greater in plots which were dominated by *Eriophorum* species than those in the blocks vegetated with dwarf-shrubs, which were drier, both in terms of peat water content, water table and humidity

A laboratory experiment comparing the success of *Sphagnum* establishment on different peat types at different water table depths (Buttler *et al*, 1998 [1++]) found that higher water tables produced significantly more *Sphagnum* growth in terms of both length and relative weight.

A laboratory experiment exploring the impact of water tables on the success of reintroduction of different *Sphagnum* species (Campeau & Rochefort, 1996 [1++]) and found significantly more capitula and higher cover for most species (except *S. fuscum*) in the high water level treatment.

Another laboratory experiment examining peat type and water table effects on growth of *Sphagnum* shoots in transplanted mats (Grosvernier *et al*, 1997 [1++]) found that, while *Sphagnum* species was the main influence over growth rate, water table was the next most important factor and interacted significantly with peat type and species.

A field experiment looked at the impacts of tree felling and drain blocking on vegetation and gas fluxes in a finish blanket bog (Komulainen *et al*, 1999a [2+]) and found that increased water tables were associated with increases in bog species (Andromeda polifolia, Vaccinium oxycoccus and V. microcarpum, *Sphagnum balticum*, *S. fuscum* and Polytrichum strictum) and a reduction in *Calluna vulgaris* and Cladonia.

A series of repeated surveys on revegetating cut-over peatland in Canada (Lavoie *et al*, 2005 [2+]) found that the there was a positive correlation between cover of *Eriophorum vaginatum* and higher water tables (shallower water table depths).

A case study comparison of drained, drain-blocked and intact sites dominated by *Eriophorum* spp. in the Yorkshire dales (Holden *et al*, 2011 [2++]) observed that the intact site, with higher water tables, supported a greater cover of *Sphagnum* that the drained or blocked sites.

A field survey of *Sphagnum* distribution across northern England (Carroll *et al*, 2009 [2++]) found that *Sphagnum* diversity and cover were significantly higher at sites with higher moisture content.

Repeated field surveys of *Sphagnum* growth rates in the North Pennines (Clymo & Reddaway, 1971 [2+]) found that plants generally elongate most in wetter pool conditions but this did not necessarily coincide with the greatest mass accumulation, *Sphagnum (capillifolium ssp.) rubellum* elongates least on hummocks yet still puts on most mass on hummocks and *Sphagnum papillosum* elongates and accumulates most in lawn settings.

Evidence statement

The following statement is supported by the evidence above:

- Peat forms where decomposition is retarded by waterlogging, so plant species which are found in peat are those which tolerate wet conditions, and form wetland communities. (Boudreau & Rochefort, 1998 [1++]); (Buttler *et al*, 1998 [1++]); (Campeau & Rochefort, 1996 [1++]); (Grosvernier *et al*, 1997 [1++]); (Komulainen *et al*, 1999a [2+]);(Lavoie *et al*, 2005 [2+]); (Holden *et al*, 2011 [2++]); (Carroll *et al*, 2009 [2++]); (Clymo & Reddaway, 1971 [2+]); (Malmer *et al*, 1994 [3+]). There are no studies that refute it.

Composition of peat deposits

A study of peat macrofossils and palynology in intact and damaged peatlands in the Forest of Bowland (Mackay & Tallis, 1996 [3-]) found that the plant remains in peat deposits were dominated near their bases by *Eriophorum vaginatum*, with some ericaceous plants and *Sphagnum tenellum* or *S. recurvum (fallax)*, with more *S. papillosum* in their centres or upper halves, with surface peat deposits reflecting the current vegetation more.

A case study of macrofossil remains in *Molinia*-dominated blanket bog in Mid Wales (Chambers *et al*, 2007a [3+]) found that lower deposits were dominated by *Eriophorum vaginatum* remains, which were replaced in the upper peat profile by undifferentiated organic matter and unidentifiable monocotyledonous remains, which were replaced over the top 10cm of peat with recognisable *Molinia* remains. Since no explanation is provided for the origin of the unidentifiable remains, it is possible that these represent *Molinia* which has decomposed beyond recognition before entering the catotelm to form peat.

A series of peat macrofossil cores were analysed from a range of deep and shallow peat areas in South Wales (Chambers *et al*, 2007b [3+]) which indicated a wide variety of different patterns of vegetation over time, across relatively short distances. The longest core was mostly unidentified organic matter with ericaceous plants, replace above with *Sphagnum*, which is replaced above again by unidentifiable organic matter. Other cores showed mixtures of unidentified organic matter, ericales, *Eriophourm*, *Molinia* and *Sphagnum* remains.

A review of peat composition and formation (Malmer *et al*, 1994 [3+]) noted that while *Sphagnum* is not essential to peat formation, historically *Sphagnum* has formed the bulk of most blanket bog peat.

Evidence statement

The following statement is supported by the evidence above:

- Blanket peat is typically composed of a variable mixture of remains of *Sphagnum* spp., *Eriophorum* spp., dwarf shrubs, unidentified organic matter and *Molina caerulea*, the balance of which varies down the peat profile and between sites over small scales. (Chambers *et al*, 2007b [3+]); (Chambers *et al*, 2007a [3+]); (Malmer *et al*, 1994 [3+]) supported by (Mackay & Tallis, 1996 [3-]). There are no studies that refute it.

Water tables and *Sphagnum* mosses

A before and after study of gully blocking in the Peak District (Burtt & Hawke, 2008 [3-]) found that local rises in water tables were accompanied by increases in *Sphagnum* mosses.

A peat profile study in the Forest of Bowland noted that (Mackay & Tallis, 1996 [3-]) noted that the study site dominated by *Sphagnum papillosum* had high mean water tables (8.4cm below the surface).

A field experiment examining *Sphagnum* re-establishment in a cut-over raised bog in Canada (Boudreau & Rochefort, 1998 [1++]) found that *Sphagnum* establishment was greater in plots which had higher peat water content, water table and humidity

A laboratory experiment explored the impact of water tables on *Sphagnum* growth (Campeau & Rochefort, 1996 [1++]) and found significantly more *capitula* and higher cover for most species (except *S. fuscum*) in the high water level treatment.

A laboratory study of *Sphagnum* growth impacts of peat type and water table (Grosvernier *et al*, 1997 [1++]) found that high water table's enhanced *Sphagnum* growth rates in most species (except *S. fuscum*).

In a Finnish field experiment (Komulainen *et al*, 1999a [2+]), tree felling and drain blocking resulted in both increased water tables and increases in *Sphagnum balticum* and *S. fuscum*.

A field experiment examining the introduction of different species of *Sphagnum*, as different fragment sizes, with different fertiliser regimes and water tables (Rochefort *et al*, 1995 [1-]) found that *Sphagnum magellanicum* formed more new capitula under a higher water regime.

A field survey of *Sphagnum* distribution in northern England (Carroll *et al*, 2009 [2++]) found higher *Sphagnum* diversity and cover at sites with higher moisture content.

A field experiment in Ireland and Estonia to introduce *Sphagnum* plugs into intact bogs (Robroek *et al*, 2009 [1+]) found that the response to water table was species specific, with bog pool species declining less under high water tables (5 cm)and hummock species maintaining or increasing cover under lower (20 cm) water tables.

Evidence statement

The following statement is supported by the evidence above:

- High water tables facilitate the growth and increase the abundance of *Sphagnum*. (Boudreau & Rochefort, 1998 [1++]); (Campeau & Rochefort, 1996 [1++]); (Grosvernier *et al*, 1997 [1++]); (Komulainen *et al*, 1999a [2+]); (Rochefort *et al*, 1995 [1-]); (Carroll *et al*, 2009 [2++]) and supported by (Burtt & Hawke, 2008 [3-]); (Mackay & Tallis, 1996 [3-]). There are no studies that refute it.

Major peat-forming plants

In the peat cores examined in the Forest of Bowland by (Mackay & Tallis (1996 [3-]) remains of drier moorland species *Hypnum cupressiforme and Empetrum nigrum, Dicranum* moss, ericaceous shrubs and *Deschampsia flexuosa* were found without *Eriophorum* or *Sphagnum* only at the surface (litter layer) of the peat mass, while ericaceous shrub remains were found throughout the profiles in association with *Eriophorum* and *Sphagnum*.

In the peat cores from South Wales examined by Chambers *et al,* (2007b [3+]), ericaceous shrubs form a sub-component of the peat profile, along with varying dominance of undifferentiated organic matter, *Eriophorum* and *Sphagnum* remains, but only become a dominant component at the upper surface of cores taken from under *Calluna*-dominated vegetation.

A study of peat accumulation rates in a Swedish bog (Gunnarsson *et al*, 2008 [2++]) found that while peat growth rate was significantly and positively correlated with *Sphagnum* cover, productivity was lowest in the areas dominated by evergreen dwarf shrubs, and cumulative accumulation of peat depth was lowest under evergreen dwarf shrubs.

Evidence statement

The following statement is supported by the evidence above:

- *Calluna vulgaris*, and other moorland plants of drier habitats, don't form blanket peat on their own, without the presence of *Sphagnum* or *Eriophorum* of other wetland plants. (Chambers *et al*, 2007b [3+]); (Gunnarsson *et al*, 2008 [2++]) and supported by (Mackay & Tallis, 1996 [3-]). There are no studies that refute it.

Molinia and peat formation

The peat cores examined in Mid Wales by Chambers *et al,* (2007a [3+]) have a majority component of unidentifiable organic matter or undifferentiated monocotyledonous material, the origin of which is not explained by the authors. They cite the presence of identifiable *Molinia* macrofossils at the top 10 cm of peat but small scale fluctuations between this material and unidentified material are not explored, and nor is the relationship with water table. It would seem likely that a proportion, if not all, of this unidentified material is derived from *Molinia* and that presence at the top 10 cm of recognisable *Molinia* remains indicates *Molinia* that has been deposited into an acrotelm layer, and has not yet decomposed to become an unrecognisable component of the catotelm.

Some of the cores examined in South Wales by the same author (Chambers *et al*, 2007b [3+]) also have large components of unidentified organic material, but one core also contains a layer containing much recognisable *Molinia*, in a matrix of undifferentiated monocotyledonous material that may or may not be *Molinia*-derived.

Evidence statement

The following statement is supported by the evidence above:

- *Molinia* can form peat on its own. (Chambers *et al*, 2007a [3+]); (Chambers *et al*, 2007b [3+]). There are no studies that refute it.

Areas requiring further study

The evidence for *Molinia* as a major peat-forming species is weak, and subject to differing interpretations of the data. More research on this topic would be valuable to understand the importance of *Molinia*-dominated blanket peat to carbon sequestration.

There is some evidence present in the review to suggest that the species found in contemporary peat macrofossil deposits approximate to NVC communities now defined as blanket bog and associated vegetation types. A total of 3 studies support this statement: (Mackay & Tallis, 1996 [3-]); (Chambers *et al*, 2007a [3+]); (Chambers *et al*, 2007b [3+]). However, this data has not been digitised and analysed, and would benefit from multivariate analysis for trends over time/depth.

Causes and impacts of degradation

This section identifies evidence considered in this review that addresses the following key question.

Key question: b) what factors (management, atmospheric deposition and climatic) affect the hydrological, structural and floristic status and composition of blanket bog, and leads to its degradation?

Presented here is evidence of the impacts of specific deliberate or accidental human interventions applied to peatlands (afforestation, peat cutting, drainage, atmospheric deposition of pollutants). Grazing and burning are specifically considered in separate and concurrent reviews. Also included here are studies of situations which are the outcomes of non-specific management interventions (changes in semi-natural vegetation, erosion or bare peat). The type of semi-natural vegetation or extent of erosion and bare peat that occurs in the upland is influenced by management, climatic and depositional factors, and therefore fall within the scope of this review. There is a clear lack of evidence in the review shortlist relating to climatic impacts, which could be addressed by existing intervention and palaeoecological studies but which were not identified (or excluded) during the sift process.

Afforestation

Impact of afforestation on water table and peat subsidence

A repeated field survey of afforested and intact peatlands in Scotland (Shotbolt *et al*, 1998 [2++]) found that peat surface subsidence had occurred in afforested bog, with half the subsidence occurring within 7 years of planting, and the oldest forestry plots had lowest surface water contents and highest surface bulk densities.

A study of the impact of afforestation on blanket peat at the same site as above (Anderson *et al*, 2000 [1++]) found that ploughed, planted plots had significantly lower water tables than unplanted controls, with differences more marked during drier weather and that plots with tree planting and drainage had significantly higher rates of surface subsidence (10.7cm) than for the drained, but unplanted, control plots (3.7cm) and that peat shrinkage occurred throughout the 1.5m profile measured.

A monitoring programme of tree felling on blanket bog in Ireland (Murphy, 2008 [3-]) noted that water table in better drained plots rose following tree felling.

Evidence statement

The following statements are supported by the evidence above:

- Ploughing and planting coniferous trees on peat lowers the peat water table and causes peat surface subsidence and compaction. (Shotbolt *et al*, 1998 [2++]); Anderson *et al*, 2000 [1++]) and supported by (Murphy, 2008 [3-]). There are no studies that refute it.

Impact of afforestation on methane emissions and carbon balance

A meta-analysis of the impact of land management changes on peatland GHG and C flux (Worrall *et al*, 2010 [2+]) found that afforestation reduced methane emissions in 7 out of 7 studies increased primary productivity in 9 out of 9 studies, but also increased soil respirational loss of CO_2 in 10 out of 13 studies.

Evidence statement

The following statement is supported by the evidence above:

- Afforestation reduces methane emissions from peatlands and increases short-term carbon sequestration. (Worrall *et al*, 2010 [2+]). There are no studies that refute it.

Impact of afforestation on blanket bog vegetation

A monitoring study of forestry clearance in Ireland (Murphy, 2008 [3-]) found that found that the vegetation composition of the ground flora under older (25-35 year old) plantations was dominated by needle litter and bryophytes (*Hypnum cupressiforme, Rhytidiadelphus loreus*, with some *Sphagnum capillifolium* and other woodland mosses), while younger (13-20 year old) plantations having a more even balance of herbs, dwarf shrubs and bryophytes more similar to intact bog (*Calluna vulgaris*, *Molinia caerulea*, Potentilla erecta, *Sphagnum capillifolium*, *Erica tetralix*).

Repeated surveys of cleared forestry in Kintyre, Scotland (Sheridan, 2008 [1++]) found that vegetation communities in felled sites with a range of felling dates showed a significant and consistent change in community from being similar to older Sitka-dominated plantation (with competitive species relating to felling Chamerion *angustifolium*, *Holcus lanatus, Dicranella sp*.) through increasing *Eriophorum vaginatum*, *Molinia caerulea* and *Potentilla erecta*, towards M19 communities supporting *Sphagnum spp., Drosera rotundifolia, Eriophorum angustifolium*, *Erica tetralix* and *Calluna*.

Evidence statement

The following statement is supported by the evidence above:

- Increasing time under forestry plantation results in greater changes in the understory community composition making it less similar to typical blanket bog vegetation. (Sheridan, 2008 [1++]) supported by (Murphy, 2008 [3-]). There are no studies that refute it.

Impact of afforestation on birds

A review of the impact of afforestation of blanket bog birds(Stroud *et al,* 1988 [4]) reported that afforestation of blanket bog peatlands replaces bog bird communities with forest bird assemblages of lower conservation value, and that higher populations of displaced birds are not maintained Birds on adjacent blanket bog are likely to be adversely affected by changes in land management due to forestry, changes in vegetation and increased predation of moorland birds by woodland or woodland edge species such as crows and foxes. A loss of 17-19% of greenshank, dunlin and golden plover were reported directly due to afforestation in Caithness and Sutherland.

Evidence statement

The following statement is supported by the evidence above:

- Afforestation of blanket peatlands impacts negatively on blanket bog bird communities of high conservation value both in, and adjacent to, plantation areas. (Stroud *et al,* 1988 [4]).

Areas requiring further study

The contention that afforestation impacts on bird populations of blanket mires is supported by a review study which references many studies. However it mentions ongoing work on forest edge effects on blanket bog birds, the results of which may now be available, along with other studies since. Additional literature review is required to affirm and update this Evidence statement.

Peat cutting

A field-based case study and laboratory study looked at evaporation dynamics of bare and naturally re-vegetated cut-over peatlands in Canada (Farrick & Price, 2009 [2+]) and found that, in the field, evaporation from bare peat was significantly higher than that for litter covered peat initially, (~ 3 mm per day compared to ~0.4-0.6 mm) but fell between 20-30 days into the season to similar levels to litter covered peat, while in the laboratory water tension in bare peat remained stable as water tables fell, but experienced a sudden decline, after a lag of 11 days, following draw-down to 30 cm, while in peat dominated by dwarf shrubs, the water tension reduced steadily with drawdown.

Areas requiring further study

It was not possible to develop any Evidence statements from the literature reflecting peat cutting, because there was little included in the review. There is little evidence available to this review on the impact of peat cutting on the hydrology and other functions of peatlands. One laboratory study indicates that bare peat in peat cuttings initially dries out rapidly when water tables are low, but then remains stable, whereas dwarf-shrub vegetated peat continues to dry out (Farrick & Price, 2009 [2+]).

There is weak evidence (Ardron, 1999 [3-]) that there are distinctive plant communities between uncut blanket bog, in peat cuttings and at the boundary of cuttings and no evidence was reviewed that indicated impacts of peat cutting on many other functions. The weakness of the evidence base for the impact of peat cutting (rather than subsequent natural re-vegetation) is probably either because it is assumed that peat cutting will result in total loss of most peatland functions or because upland peat cutting is not now a common practice, except for small-scale domestic purposes which are unlikely to be studied. More literature on the impacts of peat cutting on the hydrology and other properties of peatlands may be available from technical studies designed to facilitate peat extraction, which may not have been identified during the original literature search.

Drainage

Impact of drainage on water table

A monitoring study of deforestation in Ireland (Murphy, 2008 [3-]) noted that water tables in intact blanket bogs were generally within 5cm of the mire surface except in dry weather, but drained bogs had water tables more than 30 cm below the surface, and lower in dry weather.

A detailed case study of two blanket peat areas in the North Pennines drained 27 and 1 years previously (Stewart and Lance,1991 [2++]) found that dipwells at midpoints between grips showed no differences in hydrological properties from dipwells in intact peatlands, but that mean water tables at both sites were significantly lower for 2-2.3 m immediately downslope of the grip, but only for 0.3-1 m upslope of the grip. Water tables in these bore holes were less responsive to rainfall than those immediately above, or distant from, the grip.

A case study comparison of drained, blocked and intact peatlands in Upper Wharfedale, Yorkshire (Holden *et al*, 2011 [2++]) found that mean water table depths were significantly lower in the drained peatland (11.5 cm from the surface) than in the intact peatland (5.8 cm) , that water tables were lowest nearest the drain, but increased rapidly over 2 m either side of the drain and that water tables fluctuated more, and more rapidly, in response to storm events in the drained site than in the intact site.

A comparative survey of three areas comprising drained, blocked and intact blanket bog in Yorkshire (Wallage & Holden, 2011 [2+]) found that mean water table in the intact peatland was highest (5.8 cm from the surface) and remained at the surface longest (18% of time), compared with 10.1 cm in the drained area where water tables were at the surface for only 2% of the time.

A field experiment examining the impact of deep and shallow drainage treatments and afforestation on blanket peat in Scotland (Anderson *et al*, 1995 [1++]) found that all drainage treatments resulted in significant lowering of the water table compared with the undrained control, with intensively drained treatments having lower water tables than less intensively drained areas and after 19 years all drained areas had water tables significantly lower than in the undrained plots. A later plot experiment also found that 30 cm deep ploughing lowered water table depth.

A comparative survey of gripped peatlands in the North Pennines (Coulson *et al*, 1990 [2++]), found that water table and surface soil moisture content was higher 1.5 above the ditch than the same distance below the ditch. The overall pattern was for water tables to be near the surface at midpoints between grips, lowered slightly above the grip and lowered more deeply and over a longer distance downslope of the grip. Grips lowered water tables more and affected then for greater distances, at the lower rainfall sites.

Evidence statement

The following statement is supported by the evidence above:

- Drainage of blanket peatland lowers the overall water table compared to undrained peatlands, in a changing pattern relating to the location of the grips. (Murphy, 2008 [3-]); (Stewart and Lance,1991 [2++]); (Holden *et al*, 2011 [2++]); (Wallage & Holden, 2011 [2+]); (Anderson *et al*, 1995 [1++]); (Coulson *et al*, 1990 [2++]). There are no studies that refute it.

Impact of drainage on flood hydrographs

A re-examination of flow data from 2 drained and 2 undrained catchments in the North Pennines (Robinson, 1985 [2+]) found that the two artificially-drained catchments had flood hydrographs with significantly shorter mean response time to peak flow (flashier flow), than the catchments with natural drainage, based on data from all non-snow storm events over two years.

Holden *et al,* (2006 [2+]) studying the same site over 40 years after these data were recorded, also found that the two drained catchments had higher peaks, and significantly shorter lag times, than the control intact catchments.

A before and after study of blanket bog grip blocking in the Yorkshire Dales (Grayson & Holden, 2012b [2++]) found little evidence at catchment scale that grips had impacted storm hydrographs.

Evidence statement

The following statement is supported by the evidence above:

- The impact of drainage on the response times for storm hydrographs (flashiness) is not consistent between studies. (Holden *et al*, 2006 [2+]); (Robinson, 1985 [2+]) showed higher flashiness in drained catchments while (Grayson & Holden, 2012b [2++])indicated no differences in flashiness.

Impact of drainage on overland flow

A detailed study of 2 drained and two intact catchments in the North Pennines (Holden *et al*, 2006 [2+]) found that overland flow was far more common in the intact sites than in drained sites, and in the latter it was absent downslope of ditches and most common 2 m upslope of ditches, where the water table was highest and least variable.

Evidence statement

The following statement is supported by the evidence above:

- Drained blanket peatlands have less overland flow than intact peatlands. (Holden *et al*, 2006 [2+]). There are no studies that refute it.

Impact of drainage on peat pipes

A field survey of 160 blanket peatland sites (Holden, 2005a [2++]) found that plots on gripped hill slopes had significantly higher pipe densities (127.4 pipes km^{-1}) than those on non-gripped slopes (56.6 pipes km^{-1}), and the effect appeared to be independent of rainfall or topographic index in the catchment.

A field survey of 320 blanket peatland sites using GPR to detect peat pipes (Holden, 2006 [2++]) found that there was a strong, significant, linear, positive correlation between peat pipe density and the number of years a peatland had been drained (km pipes per km^2 = 2.1 x number of years drained + 41.6) and a significant correlation indicating that pipe cross-sections and total pipe volume were larger in sites drained for longer.

Evidence statement

The following statement is supported by the evidence above:

- Drained peatlands have a higher density and volume and larger size of peat pipes than undrained peatlands. (Holden, 2005a [2++]); (Holden, 2006 [2++]). There are no studies that refute it.

Impact of drainage on DOC concentrations

A controlled before and after study in the North Pennies comparing one gripped, one blocked and 2 intact peat catchments (Gibson *et al*, 2009 [2+]) found that drained sites had significantly higher absorbance and DOC concentrations than intact sites.

A systematic review of the impacts of drainage and rewetting on peatland GHG flux and c dynamics (Bussell *et al*, 2010 [1++]) reported that, based on analysis of eight effects from four studies, drained peatlands had significantly higher DOC concentrations in soil water than undrained examples.

A treatment/control comparison study in the field and laboratory examined drained and undrained blanket mire in Yorkshire Dales (Wallage *et al*, 2006 [2+]) and found that DOC concentration values from drained peat were significantly greater than intact peat.

Evidence statement

The following statement is supported by the evidence above:

- Drained blanket peatlands have higher concentrations of DOC in their peat water. (Gibson *et al*, 2009 [2+]); (Bussell *et al*, 2010 [1++]); (Wallage *et al*, 2006 [2+]). There are no studies that refute it.

Impact of drainage on blanket bog vegetation

A case study of two drained blanket bog sites, in the North Pennines (Stewart and Lance,1991 [2++]) found that *Sphagnum* was absent near both sides of the grips, while *Eriophorum* was reduced more along the downslope edge, and *Calluna* was evenly distributed. Analysis of former vegetation records at the site showed that *Calluna* increased on the downslope side of the drain 8 years after drainage, *Eriophorum* declined downslope after 8 years and upslope after 15 years, and after 19-23 years *Sphagnum* capillifolium had been almost completely lost from near the drains and from the rest of the transect. Liverworts at the drain edge declined after 8 years to two thirds of the typical site abundance while lichens increased at the lower drain edge after 19 years. A survey of a wider sample of drained blanket bogs in the area indicated that *Eriophorum angustifolium*, E. *vaginatum*, *Sphagnum* capillifolium and *S. papillosum* were significantly less frequent, and *Calluna* shoot length, cover of *Rubus chamaemorus* and of lichens were greater in a zone up to 2 m downslope of the grip when compared with a reference plot 10 m upslope of the grip. *Trichophorum cespitosum* was more frequent 0.5 m upslope of the grip than at the 10 m upslope plots.

A comparative survey of gripped peatlands in the North Pennines (Coulson *et al*, 1990 [2++]) found that vegetation composition near the grips was more affected in the lower sites surveyed, with large increases in grasses at the expense of *Calluna* downslope of the grip, while there were few changes at the upper, more bryophyte-dominated, sites at the distances measured.

A comparative survey of vegetation along transects running perpendicular to open grips, and those blocked for 3, 4, 5 and 11 years (Bellamy *et al*, 2012 [2+]) found that for most sites, the index of wetter vegetation was highest furthest from open drains and indicated drier vegetation close to the drain.

Evidence statement

The following statement is supported by the evidence above:

- Drained peatlands have a lower frequency or abundance of *Sphagnum* and *Eriophorum* spp., and a higher frequency or abundance of lichens or grasses, especially close to the drain. (Stewart and Lance,1991 [2++]); (Coulson *et al*, 1990 [2++]); (Bellamy *et al*, 2012 [2+]). There are no studies that refute it.
- Drained peatland may show higher or lower abundance of *Calluna* adjacent to grips, the response varying between sites. (Stewart and Lance,1991 [2++]) showed an increase in *Calluna* vigour while (Coulson *et al*, 1990 [2++])showed a reduction. Other site factors (altitude, grazing) may be interacting to influence this response.

Impact of drainage on erosion

A field survey of drainage grips in the Pennines and Scotland (Holden *et al*, 2007 [2+]) found that drains with slopes under 2o were commonly infilling and only rarely eroding, while those with 4o slopes or more were most commonly eroding and rarely infilling. Slopes over 5o have a wider range of erosion values and can have 1 m2 or more of cross sectional area eroded. Erosion was often most extensive at confluences.

Evidence statement

The following statement is supported by the evidence above:

- Moorland drains on steep slopes (>4o) tend to erode, while those on gentler slopes tend to infill, and there is more erosion at drain confluences that along lengths. (Holden *et al*, 2007 [2+]). There are no studies that refute it.

Impact of drainage on methane emissions

A systematic review of the impacts of drainage and rewetting on peatland GHG and C fluxes (Bussell *et al*, 2010 [1++]) found, based on 27 studies of methane in drained and intact peatlands, that drained peatlands emitted significantly less CH_4 (by ~8mg CH_4 m^{-2} day^{-1}) than intact peatlands.

A meta-analysis of comparative field studies looking at land management impacts on peatland GHG and C flux (Worrall *et al*, 2010 [2+]) found that 12 out of 13 studies showed reductions in methane emissions following drainage.

Evidence statement

The following statement is supported by the evidence above:

- Drained blanket peatlands emit less methane than undrained ones. (Bussell *et al*, 2010 [1++]); (Worrall *et al*, 2010 [2+]). There are no studies that refute it.

Areas requiring further study

There is one study which suggests that while there is weak evidence for higher gross respiration (including plant roots) there is no difference in net ecosystem respiration between drained peatlands and undrained peatlands (Bussell *et al*, 2010 [1++]), while another study (Worrall *et al*, 2010 [2+]) suggests that the drained peatlands emit more CO_2 than undrained peatlands. The former study took into account magnitude of impacts and rejected poorer quality studies, while the latter assessed more studies, but only examined direction of change and did not quality-assess studies.

The evidence shows that drainage increases DOC concentrations in soil water, suggesting that this may be an important pathway for C loss following drainage, yet there were no studies available to compare the impact of drainage on DOC export from blanket peatland catchments. Further review or research into the impact of drainage on DOC loss would indicate the importance of this as a pathway for C loss from drained peatlands.

Atmospheric deposition of pollutants

Impact of sulphur deposition on *Sphagnum*

An outdoor chamber experiment (Ferguson *et al*, 1978 [1+]) exposed *Sphagnum* to sulphate or bisulphate in solution or as gaseous SO_2 equivalent to 1970's urban pollution concentrations, or 1950's levels in the Peak District. They found that *Sphagnum* growth was negatively affected by all three forms of sulphur pollution. In solution bisulphite was more harmful to growth and chlorophyll content than sulphate, with *S.recurvum* (now fallax) most tolerant and *S.tenellum* most sensitive. Gaseous SO_2 reduced growth in four *Sphagnum* species but not in *S.magellanicum* and had no effect on chlorophyll content.

A survey of *Sphagnum* distribution in relation to other environmental variables (Carroll *et al*, 2009 [2++]) found higher *Sphagnum* diversity and cover was associated with higher peat pH, but found no significant correlations between *Sphagnum* abundance or diversity and extractable sulphate content.

Evidence statement

The following statement is supported by the evidence above:

- High past rates of deposition of acidic sulphur compounds will have slowed the growth rate several typical blanket bog *Sphagna*. (Ferguson *et al*, 1978 [1+]).

Impact of nitrogen deposition on blanket bog vegetation

A field experiment applying dry and wet ammonia deposition to blanket bog vegetation in Scotland (Sheppard *et al*, 2011 [2++]) found that dry ammonia deposition at 20–56 kg NH3-N ha^{-1} yr^{-1} led to almost total loss of *Calluna vulgaris*, *Sphagnum* capillifolium and *Cladonia portentosa* while *Eriophorum vaginatum* and *S.fallax* and S.*papillosum* were less damaged, and wet N deposition caused significant decreases in *S. capillifolium* only.

Evidence statement

The following statement is supported by the evidence above:

- High levels of dry atmospheric deposition of ammonia will alter *Sphagnum* communities to remove some species of *Sphagnum* completely, or increase 'undesirable' nutrient-tolerant species such as *S. fallax*, and can damage the health of plants of drier moorland (*Calluna vulgaris* and *Cladonia portentosa*), while wet deposition of ammonium reduced cover of one *Sphagnum* species. (Sheppard *et al*, 2011 [2++]). There are no studies that refute it.

Areas requiring further study

More research has been conducted on the impacts of nitrogen deposition on *Molinia caerulea*, *Calluna vulgaris* and probably also on other species, although some of this has been outside of blanket bog habitats. There were no other studies included in this review to indicate the impact of atmospheric deposition of pollutants on other blanket bog plants.

The field survey of *Sphagnum* distribution and relationship with environmental parameters across the Pennines (Carroll *et al*, 2009 [2++]) found no significant correlations between *Sphagnum* abundance or diversity and extractable ammonium or extractable sulphate content of peat. This may indicate either that the levels of ammonia and sulphate deposition currently occurring across much of the Pennines are insufficient to elicit a detectable response, that deposition rates are too uniform across the area to elicit a variable response required to detect a correlation, or that extractable ammonium or sulphate in peat is a poor indicator of current rates of atmospheric deposition. More research may be required to determine the extent to which these explanations apply.

The literature analysed for this review represents only a few key papers relating to the impact of air pollution on semi-natural habitats. A review of air pollution (NEGTAP, 2001) noted that while sulphur pollution impacts had ameliorated, bog communities had seen increases in plants associated with higher N requirements. A more recent UK-wide project (Review of Transboundary Air Pollution – RoTAP, 2012) has examined the impacts and extent of acidification, eutrophication, heavy metals and low-level ozone pollution, including impacts on semi-natural vegetation. This report concluded that declining species richness in moorlands, and replacement of pollution sensitive bryophytes with more pollution-tolerant communities was a relatively recent phenomenon. However, the links to pollutant deposition were correlatory, and causal relationships required further experimental studies to establish. It notes that while 40-50 % of the area of UK bogs are subject to N deposition that exceed critical load values (10 kg N ha^{-1} yr^{-1}) vegetation responses to deposition are a continuum, and do not take the form of a critical threshold. However, they recognise that ammonia gas appears to be more damaging to moorland vegetation that wet ammonium deposition and a new threshold is identified of 1 µg m-3 above which impacts on bryophytes would be expected. While some 69% of the UK is identified as being above this threshold, the majority of English uplands appear to be below it, suggesting that N pollution should not present an insurmountable obstacle to bog restoration.

Changes in semi-natural vegetation

By the definition of active, functioning blanket bog used for this review (using CSM thresholds) changes to semi-natural vegetation that prevent a bog from meeting CSM species cover targets, which are used to define good condition, will be defined as floristic degradation (for example, *Molinia* dominance). This does not necessarily mean that the other functions of the bog are degraded, although they may be affected. These impacts are explored in the following sub-sections.

Impact of *Calluna* dominance on peat pipes

A field survey used GPR to detect and map peat pipes in 160 sites throughout the UK, and also conducted a case study at Moor House, North Pennines, and a laboratory experiment looking at the impact of *Calluna* on peat pipes and changes in macroporosity due to rainfall (Holden, 2005b [2+]). The study found that plots with *Calluna* and bare peat had significantly higher frequency of peat pipes than plots without these features, and the case study found that, of two areas with dominated by either *Calluna* or *Eriophorum* (and at different altitudes) but with otherwise similar topographic features, more pipes were found in the lower *Calluna* dominated plots. The laboratory study found that peat under *Calluna* increased its macropore flow in response to rainfall more than peat from under *Sphagnum*, *Eriophorum* or bare peat, where macropore flow remained stable.

Evidence statement

The following statement is supported by the evidence above:

- Blanket peatlands dominated by *Calluna vulgaris* have more frequent and dense peat pipes, and higher macropore flow lower in the soil, which increases with ongoing high rainfall, unlike that for peat under *Eriophorum*, *Sphagnum* or bare ground. (Holden, 2005b [2+]). There are no studies that refute it.

Impact of different vegetation types on overland flow speeds

A comparative field survey explored the overland flow speeds associated with bare peat, *Sphagnum*, *Eriophorum* or a mix of these 2 genera (Holden *et al*, 2008 [2++]) and found that overland flow speeds were consistently and significantly higher over bare peat than over vegetated surfaces, and those over *Sphagnum* -dominated vegetation were significantly slower than for other vegetation types.

Evidence statement

The following statement is supported by the evidence above:

- *Sphagnum* -dominated blanket bog vegetation has slower rates of overland flow during storm conditions than blanket bog dominated by *Eriophorum* or a mix of *Eriophorum* and *Sphagnum*. (Holden *et al*, 2008 [2++]). There are no studies that refute it.

Vegetation impacts on macropore flow

A laboratory study looking at rainfall impacts on macropore flow under different moorland vegetation types found that (Holden, 2005b [2+]) *Sphagnum* -dominated peat blocks initially had a significantly higher proportion of macropore flow through 0.05-2 mm pore sizes than other vegetation types, and Calluna-dominated blocks had significantly higher proportional of flow through macropores >2 mm.

A comparative survey of macropore flow under different blanket peatland vegetation types in the North Pennines (Holden, 2009a [2+]) found that under bare peat, *Eriophorum* or Calluna, macropore flow declined at deeper soil depths, whereas under *Sphagnum* this component of flow either maintaining or increased as a proportion of overall flow rate with increased peat depth.

This study is more fully described in Holden *et al,* (2001 [2++]) which reported that *Sphagnum* sites have significantly larger proportions of flow through macropores than other vegetation types and different patterns with depth. They also found that saturated hydraulic conductivity under Bare peat, and *Eriophorum*-dominated and Calluna-dominated peat was generally highest at the peat surface, slightly lower at 5 cm, and falling rapidly at 10 and 20 cm from the surface, while under *Sphagnum* there was a sharp drop in conductivity from 0-5 but below this conductivity remained stable, and higher than other vegetation types.

Evidence statement

The following statement is supported by the evidence above:

- *Eriophorum vaginatum*-dominated and *Calluna vulgaris*-dominated vegetation have lower peat macropore flow at deeper layers (10-30cm) compared with peat under *Sphagnum* -dominated vegetation. (Holden, 2005b [2+]); (Holden, 2009a [2+]); (Holden *et al*, 2001 [2++]). There are no studies that refute it.

Impact of *Calluna* dominance on DOC

A comparative survey study of sites affected by wildlife, re-vegetation, and intact sites with different semi-natural vegetation (Worrall *et al*, 2011 [2++]) found that lowest DOC flux was from the *Eriophorum* dominated site (13 tonnes C km^{-2} yr^{-1}), and highest was from the dwarf shrub dominated site with managed burning (96 tonnes C km^{-2} yr^{-1}), while bare peat and re-vegetated sites varied between these extremes.

A survey of water colour and DOC in blocked and open drainage grips in blanket bogs (Armstrong *et al*, 2008 [2-]) found that vegetation type was the best predictor of variation in DOC and water colour at both absorbance levels, with Calluna-dominated sites being associated with highest DOC and water colour when all grip types were combined. This appeared to interact with burning, in that un-burnt *Calluna* sites had the highest levels of DOC.

This data is revisited in Armstrong *et al,* (2010 [2+]) and additional multivariate analysis indicates that concentrations of colour (400nm absorbance) and DOC were significantly positively related to easting, duration of blocked, drain cross sectional area, grazing and heather dominance and negatively related to rainfall, blocking, slope (400nm colour only) and drain depth (DOC only).

Evidence statement

The following statement is supported by the evidence above:

- Blanket peat dominated by *Calluna vulgaris* tends to have higher DOC export through its drainage waters (Worrall *et al*, 2011 [2++]), and higher DOC concentrations in its grips (Armstrong *et al*, 2008 [2-]); (Armstrong *et al*, 2010 [2+]), than blanket peat dominated by other vegetation. There are no studies that refute these findings.

Impact of vegetation type on methane emissions

A controlled environment incubation experiment of large peat cores from blanket bog in North Wales (Green *et al*, 2011 [2++]) found that under raised water tables different plants were associated with significantly different emissions of methane, being lowest in *Sphagnum* papillosum-dominated vegetation and 2-4 times higher under *Calluna* and *Eriophorum*, with *Calluna* emitting more under warmer climates. Net ecosystem exchange was lowest in *Sphagnum* or *Eriophorum* and 4-5 times greater in the *Calluna mesocosms*, and GWP was lowest in *Sphagnum* , twice as high under *Eriophorum* and 3 times as high under Calluna.

Evidence statement

The following statement is supported by the evidence above:

- It is suggested that blanket bog vegetation dominated by *Calluna* and *Eriophorum vaginatum* are likely to have larger annual methane emissions, and larger overall contribution to global warming, than those dominated by *Sphagnum* papillosum, and this effect is likely to be exacerbated by warmer climates. (Green *et al*, 2011 [2++]). No studies refute this statement but this has yet to be proved in the field.

Areas requiring further study

There are no studies available to this review which indicate the impact on blanket peat function of dominance of *Molinia caerulea*. *Molinia* is seen as undesirable in terms of biodiversity, but there is no evidence whether its dominance may be beneficial or detrimental to functions such as peat formation, maintaining water quality, ameliorating runoff or GHG fluxes. Further review or research would help to inform the wider impacts of the current efforts to control this species.

There were also no studies which allowed a comparison of the impact of transpiration by dry moorland vascular plants on peat hydrological function. There is one study (Farrick & Price, 2009 [2+]) which indicate that dwarf shrubs reduce peat moisture content lower down the peat profile than is observed in bare peat. A further study (Clay *et al*, 2009) reported significant increases in water table following removal of moorland vegetation (presumably *Calluna*) by burning, and that rotationally burnt plots had higher water tables than plots with no burning for 50 years, but did not provide details of the vegetation type, structure or biomass, or clearly describe the number of years since the most recent burn. Since high water tables are needed to preserve peat, lowering of water tables by vascular plant transpiration might be expected to accelerate peat decomposition. Conifers (which like *Calluna* are evergreen vascular plants) have been shown to lower water tables and increase subsidence (Shotbolt *et al*, 1998 [2++]). If drying of peat by vascular plant transpiration were better understood it could help to explain the relationships observed between *Calluna* dominance and DOC and inform management to reduce carbon loss, water colour and improve bog condition in terms of biodiversity.

Gullying and hagging

Gullies are drainage channels through peatlands and are likely to be natural features. It has long been suggested that anthropogenic factors can increase the rate of gully formation. Gullies in peatlands are often described in terms of their extent of branching, from unbranched, linear gullies (type 2 erosion), to highly branched, reticulate gullies (Type 1 erosion, see Bower, 1961). Where branches of gullies join they may leave uneroded blocks of peat isolated from the rest of the peat mass. These are known as haggs. Gullies and haggs may have areas of bare peat, or may be partially, or entirely vegetated. As such, these features are considered separately from erosion of bare peat.

Timing of onset of gully erosion

A study of peat macrofossils at intact, gullied and hagged sites in the Forest of Bowland (Mackay & Tallis, 1996 [3-]) concluded that the vegetation has remained broadly unchanged since the early 19th century, except for the gradual loss of *Sphagnum* from the gully side and hagg top sites, and interprets this as meaning that the site was probably eroded since this time.

A study of erosion distribution and rates in the peak district (Phillips *et al*, 1981 [2+]) extrapolated current assumed rates and extent of erosion to indicate that there was probably gradual erosion at stream headwaters into the peat mass, but that rapid extension of the gully networks began after 1770 AD.

Evidence statement

The following statement is supported by the evidence above:

- Gully erosion of blanket peatlands in northern England accelerated during the late 18th/early 19th centuries. (Phillips *et al*, 1981 [2+]) supported by (Mackay & Tallis, 1996 [3-]). There are no studies that refute it.

Topographic relationships in peat erosion

A study of the distribution of gully and hagg erosion in the Peak District (Phillips *et al*, 1981 [2+]) found that within parishes, the extent of peat erosion was positively correlated with extent of elevated and steeply sloping ground. Branching or reticulate erosion (type 1) was associated with higher flatter ground and more erosion of peat margins, while linear (type 2) gullying was associated with lower, more sloping ground and more intact peat margins.

A field survey of soil erosion in upland England and Wales (McHugh *et al*, 2000 [2+]) found an estimated 18,025 ha of erosion driven by water (including gullying and hagging in blanket peatlands). Gully depth increased with increasing altitude and slope and in convex catchments, and was associated with heath/bog and bog vegetation. Extent of erosion was positively correlated with elevation and negatively correlated with slope (ie most prevalent on high flat areas). Erosion was more prevalent on peat soils, followed by wet mineral soils, followed by other mineral soils.

A case study of peat erosion in the Cheviot Hills (Wishart and Warburton, 2001 [3-]) found that anastomosing (reticulate) erosion was associated with high flat ground, linear erosion with more uniform, steeper, slops, and dendritic (branched) erosion gullies were found in catchment basins.

Evidence statement

The following statement is supported by the evidence above:

- Severity of gullying and hagging is associated with higher, flatter areas, with reticulate (type 1) erosion on flatter tops, and linear (type 2) erosion on more sloping ground. (Phillips *et al*, 1981 [2+]); (McHugh *et al*, 2000 [2+]) supported by Wishart and Warburton, 2001 [3-]). There are no studies that refute it.

Impact of gullying and hagging on water table

A comparative field study of the hydrology of drained and intact catchments (Holden *et al*, 2006 [2+]) found that water movement through an eroded peat catchment passes through deeper peat layers (43% through layers below 50 cm deep) compared to intact and drained catchments where flows are dominated by surface (0-1 cm) and shallow (1-5 cm) flows and or by sub-surface flows (5-10cm and 10-50cm) respectively, and lower water tables in the two drained (which includes the eroded catchment) than the intact catchments.

A peat macrofossil and palynological study of intact, gullied and hagged peat (Mackay & Tallis, 1996 [3-]) recorded that mean water tables were too low to be measured for most of the year (at least 39-55 cm below the peat surface) in the peat hagg, intermediate in the gullyside site (25.1 cm below surface) and highest in the intact peatland (8.4 cm below surface).

Evidence statement

The following statement is supported by the evidence above:

- Water table in peatlands is lowered by gully/hagg erosion. (Holden *et al*, 2006 [2+]) supported by (Mackay & Tallis, 1996 [3-]). There are no studies that refute it.

Erosion of bare peat

Rate of surface lowering in bare peat areas

A study of rates of erosion of bare peat using erosion ‘pins’ (straws) in the Peak District (Phillips *et al*, 1981 [2+]) found that bare peat typically loses 5-10mm per year, rising to 40-60 mm in some situations, such as at eroding peat margins.

A study of re-vegetation of bare peat in the Peak District (Buckler, 2007 [2-]) observed that peat erosion continued on bare peat where re-vegetation was no successful.

A comparison of the C budgets for vegetated, bare and re-vegetated peat (Worrall *et al*, 2011 [2++]) found that bare peat surfaces consistently subsided by 1.9 to 6.2 cm each year.

A study examining rates of surface lowering using a pin quadrant in the Peak District (Anderson *et al*, 1995b [2-]) reported that bare peat surfaces reduced in height significantly faster than surfaces with vegetation, litter or ‘roots’. However, this contention does not appear to be supported by the data presented.

A study of wind erosion on a bare peat flat in the North Pennines (Warburton, 2003 [2+]) estimated an annual erosional loss rate of erosion rates of 0.46 and 0.48 tonnes ha^{-1} (equating to ~47mm per year), but is subject to assumptions about the source area of trapped material.

A nationwide survey of erosion gullies, including those in peat, using transects of measurements (McHugh *et al*, 2000 [2+]) found no significant erosional losses of peat over 2 years.

A case study of peat erosion in the Cheviot Hills (Wishart and Warburton, 2001 [3-]) found little or no change when comparing photographs of peat erosion taking from the 1920's, 1950s, 1980s and 1990s.

Evidence statement

The following statement is supported by the evidence above:

- Bare peat surfaces rapidly recede vertically (up to 62 mm per year). A total of 5 studies (4 from the Peak District and one case study of an eroding peat flat) support this statement: (Phillips *et al*, 1981 [2+]); (Buckler, 2007 [2-]); (Worrall *et al*, 2011 [2++]); (Warburton, 2003 [2+]) supported by (Anderson *et al*, 1995b [2-]). However two studies, comprising a national survey (McHugh *et al*, 2000 [2+]) and a case study of the Cheviot Hills (Wishart and Warburton, 2001 [3-]) found no detectable changes in erosion features in the short or long term.

Overland flow over bare peat

A comparative field survey of overland flow rates over different blanket bog vegetation and bare peat (Holden *et al*, 2008 [2++]) found that overland flow was consistently and significantly higher over bare peat than over vegetated surfaces.

Evidence statement

The following statement is supported by the evidence above:

- Overland flow over bare peat is faster than over vegetated peat. (Holden *et al*, 2008 [2++]) and no studies that refute it.

Water tables in bare peat

A case study of the impacts of natural re-vegetation on water dynamics in a cut-over peatland in Canada (Farrick & Price, 2009 [2+]) and found that, in the field, evaporation from bare peat was significantly higher than that for litter covered peat initially, (~ 3 mm per day compared to ~0.4-0.6 mm) but fell between 20-30 days into the season to similar levels to litter covered peat, while in the laboratory water tension in bare peat remained stable as water tables fell, but experienced a sudden decline, after a lag of 11 days, following draw-down to 30 cm, while in peat dominated by dwarf shrubs, the water tension reduced steadily with drawdown.

Evidence statement

The following statement is supported by the evidence above:

- In drought conditions bare peat loses water from its surface rapidly, but retains it at depth. (Farrick & Price, 2009 [2+]) and there are no studies that refute it.

Impact of bare peat on carbon loss by soil respiration

A study in the Peak District of carbon budgets in bare, vegetated and re-vegetated blanket peat (Worrall *et al*, 2011 [2++]) found that the bare areas lost intermediate amounts of DOC (around half of the dwarf shrub site) and the largest amount of POC (155-206 tonnes C km^{-2} yr^{-1}) with near-zero or moderate emissions of CO_2.

A study examining the impact of re-vegetation, lime, and fertiliser on peat (Caporn *et al*, 2007 [1+]) observed low background levels of CO_2 emissions in bare peat compared to formerly vegetated soils, which increased less when treated with lime and fertiliser.

Evidence statement

The following statement is supported by the evidence above:

- Bare peat loses significant amounts of POC, moderate amounts of DOC, does not emit much CO_2 (Worrall *et al*, 2011 [2++]), and has low biological activity (Caporn *et al*, 2007 [1+]). No studies were considered that refute these findings.

Areas requiring further study

The rate of erosional loss from peat in gullies, edges of peat masses and from other bare peat areas varies with location, and the prevalence of studies in the Peak District may give a bias towards more actively eroding sites, which are more likely to be studied since they are likely to benefit most from restoration management. Erosion rates in natural or long-established gullies may be low, and this suggests that not all gullies may need to be blocked to ensure the stability of the peatland.

Impacts of restoration

This section identifies evidence considered in this review that addresses the following key question.

Key question: d) what interventions are required to restore a degraded blanket bog to a functioning and active blanket bog system with abundant peat-forming species, and over what timescale?

The evidence base is not available to indicate the timescales or interventions required for full recovery of degraded blanket bog to be indistinguishable from intact bog. Presented here is evidence indicating how different restoration techniques impact on the function and characteristics of blanket peatlands in various states of degradation. Many of these restoration interventions could be seen as a hierarchy of interventions which restore ever more function. Where peat is actively eroding or absent, then re-vegetation may restore some functions, but leave topographic degradation features that continue to affect the water table. These are then the subject of management of water table, which may impact on a different range of functions, but may not fully restore the desired vegetation characteristics. These may then become the focus of efforts to establish more appropriate blanket bog communities. From different starting points, other restoration efforts, such as deforestation, may follow a different path.

Deforestation

Vegetation recovery following felling

Monitoring of deforestation effects on blanket peatland in Ireland (Murphy, 2008 [3-]) indicated that younger plantations (13-20 years old) on felling had ground flora more similar to intact bog, than older plantations (25-35 years old).

A four year study of trees felled at different ages, and at different times in Kintyre, Scotland (Sheridan, 2008 [1++]) found that younger Picea sitchensis plantations had vegetation more similar to the M19 NVC (blanket bog) communities.

Evidence statement

The following statement is supported by the evidence above:

- Felling coniferous trees on blanket peatland is more likely to result in blanket bog vegetation recovery where the plantation is younger. (Sheridan, 2008 [1++]) supported by (Murphy, 2008 [3-]). There are no studies that refute it.

Disposal of forestry waste on felling

A study of the impact of different forestry waste disposal methods on cleared blanket bog in Kintyre, Scotland (Sheridan, 2008 [1++]) found little difference between types of post felling treatment (chipping, removal, leaving chain sawed brash) and best recovery of blanket bog species after longer periods following felling, on deeper peat depths and on gentler slopes. Also, while thicker layers of woodchip resulted in lower covers, the effect was more likely to delay recovery of blanket bog species, by 2-4 years, rather than prevent it.

Evidence statement

The following statement is supported by the evidence above:

- The practise of felling trees to waste, and disposing of waste on site need not prevent recovery towards blanket bog vegetation. Also blanket bog vegetation will recover more quickly, and to more characteristic vegetation, where the ground is flatter, wetter and where forest residues are thinner. (Sheridan, 2008 [1++]) There are no studies that refute these statements.

Areas requiring further study

The impact of deforestation on carbon and GHG budgets is reported as being unlikely to result in improved C or GHG flux (Worrall *et al*, 2010 [2+]) but this intervention has the lowest effective sample size of all analyses in this study and may represent short-term measurements. A further two studies (Komulainen *et al*, 1999a [2+] & Vasander *et al,* 2003 [2-]) applied both felling and drain blocking treatments, and so the impact of these cannot readily be separated. Vassander *et al,* 2003 [2-]), reported water quality benefits suggesting that felling and ditch blocking caused temporary increases in P due to fertiliser applied to the forest, then caused drastic reductions in suspended solids and nitrate-N concentrations. Further research is needed to elucidate the impacts of deforestation on GHG and C flux in peatlands, but would also benefit from comparison with longer term analysis of the impact of peatlands in a forested condition.

Given the impact of afforestation on water tables, deforestation could be expected to raise water tables, thus preventing peat decomposition and providing conditions for recovery of blanket bog communities and functions. Additional review or research might help to indicate the extent to which felling alone is required to restore bog functions, and where additional interventions are required.

Re-vegetation of bare peat

Success of, and conditions for, re-vegetation of bare peat.

A field experiment in the Peat District looking at the impacts of fertiliser, lime and live vegetation mulch on the establishment of transplanted *Eriophorum* spp. and moorland grasses on bare and trampled peat (Anderson *et al*, 1995b [2-]) found that fertiliser increased cover of transplanted species and reduced loss of moss cover over winter, and mulch increased cover of mosses and other species. Fertiliser and lime appeared to reduce bare ground in trampled *Eriophorum* areas. Other unreplicated trials in this report all suggest that it is possible to re-vegetate bare peat using predominantly species of drier moorland and grasses.

A study looking at use of geojute, brash and reseeding on bare peat in the Peak District (Anderson *et al*, 2011b [2-]) found that all seeding and/or heather brash treatments increased vegetation cover from 0-10% to 60-90% after 3 years, compared to declining cover in untreated plots. Initially ‘nurse’ grasses increased followed *Calluna*. In seeded fertilised and limed plots application of geojute increased heather cover over plots with brash.

A series of studies looking at use of lime, fertiliser, brash, geojute and seeding on bare peat in the Peak District (Buckler, 2007 [2-]) found that in the absence of grazing lime/ fertiliser and seed resulted in 40% mean vegetation cover after 3 years. *Festuca ovina, Agrostis castellana* and *Deschampsia flexuousa* established well, especially with heather brash, while lowland species performed poorly as nurse grasses. Heather brash encouraged *Calluna* establishment and geo-jute improved grass establishment on gully sides.

A field experiment in the Peak District, examining lime, fertiliser and seeding treatments on bare peat (Caporn *et al*, 2007 [1+]) found that application of lime or lime and fertiliser had a significant positive effect on grass establishment, with the effect of lime continuing after 8 months.

A field experiment in the North Pennines looked at impacts of disturbance, lime, fertiliser and seeding on re-vegetation of bare peat (Gore & Godfrey, 1981 [2-]) and found that, while lowland grasses died, Deschampsia flexuousa survived after several years and was encouraged by phosphorus and/or lime, and that N fertiliser treatment (regardless of N source type or digging) produced the greatest cover of mixed grasses, with agricultural grasses gradually declining over time.

A field experiment looked at the impacts of cultivation and fertiliser on vegetation establishment on bare burnt peat using a range of species in the North York Moors (Bridges, 1985 [2++]) and found that *Festuca spp, Agrostis capillaries* and *Deschampsia flexusosa* germinated well and responded well to both cultivation and fertiliser treatment, while, Holcus lanatus, Lotus *corniculatus* and *Poa* *pratensis* did not survive or germinated poorly. Sown *Calluna* failed to germinate but cultivation treatments and fertiliser treatments enhanced volunteer establishment of Calluna.

A field experiment explored the re-vegetation of disturbed peat and other substrates in the Peak District (Skeffington *et al*, 1997 [1+]) and found that fertiliser and lime application increases likelihood of establishment and cover of vegetation on formerly bare and macerated peat. Overall cover effects continued to persist 17 years after treatment.

Laboratory and field experiments in the Peak District (Richards *et al*, 1995 [1+]) examined the impacts of peat type, fertiliser and lime on *Eriorphorum angustifolium* establishment on bare peat and found that plants grown first in pots, especially in ericaceous compost, performed better on transplantation to the field than directly introduced plants, and that fertiliser and lime, or alginure soil improver, encouraged growth better than no treatment or fertiliser alone. Moderately acid conditions (pH 3.7) produced better growth responses than extremely acid conditions (2.9) independent of calcium availability.

A series of field experiments on cut over peat in Germany (Sliva & Pfadenhauer, 1999 [1++]) found that fleece, geojute and *Calluna* brash materials significantly increased germination of E. *angustifolium*, *Molinia caerulea* and *Calluna vulgaris*, while E. *vaginatum* germinated well on both bare and uncovered ground. Fertiliser application increased the number and spread of shoots of *Carex rostrata* and *E. angustifolium*. Fertilised plots showed spontaneous germination of *Rhynchospora alba*, *Drosera intermedia, Molinia caerulea, Calluna vulgaris* and *Betula carpatica*, but only fertiliser treatments containing P significantly improved germination of plants.

Tallis & Yalden (1983 [2-]) examined the impact of bituminous soil stabilisers and Larix or *Calluna* brash application on re-vegetation of bare peat in the Peak District and found that that it is possible to establish plants of heather on bare peat and mineral soil in the Peak District.

Evidence statement

The following statements are supported by the evidence above:

- Re-vegetation of bare blanket peat is possible, using *Calluna vulgaris*, grasses, or *Eriophorum angustifolium*. (Caporn *et al*, 2007 [1+]); (Skeffington *et al*, 1997 [1+]); (Richards *et al*, 1995 [1+]); (Bridges, 1985 [2++]); (Sliva & Pfadenhauer, 1999 [1++]) and supported by (Anderson *et al*, 1995b [2-]); (Anderson *et al*, 2011b [2-]); (Buckler, 2007 [2-]); (Gore & Godfrey, 1981 [2-]); (Tallis & Yalden, 1983 [2-]). There are no studies that refute it.
- Addition of both lime and fertiliser enhances the success of nurse grass, *Eriophorum angustifolium* and *Calluna vulgaris* establishment. (Caporn *et al*, 2007 [1+]); (Richards *et al*, 1995 [1+]); (Skeffington *et al*, 1997 [1+]); (Bridges, 1985 [2++]); (Sliva & Pfadenhauer, 1999 [1++]) and supported by (Anderson *et al*, 1995b [2-]); (Buckler, 2007 [2-]); (Gore & Godfrey, 1981 [2-]). There are no studies that refute it.
- Plants of lowland situations, such as agricultural grasses or legumes, are less likely to germinate and survive than those found naturally in uplands. (Bridges, 1985 [2++]) supported by (Buckler, 2007 [2-]); (Gore & Godfrey, 1981 [2-]). There are no studies that refute it.

Impact of re-vegetation on CO_2 emissions

A laboratory comparison of respiration responses in vegetated and un-vegetated peat soils(Caporn *et al*, 2007 [1+]) found that application of lime and fertiliser stimulated larger CO_2 emissions on formerly vegetated soils than on bare ones, and that both exceeded the low background level of respiration in both untreated bare and vegetated soils.

A comparison of the carbon budget for vegetated, bare and re-vegetated peat in the Peak District (Worrall *et al*, 2011 [2++]) found that re-vegetated sites varied from being a strong sink, a weak sink, a moderately strong source or varying from source to sink between years, while the bare peat sites were either a negligible sink, or a moderate source of CO_2.

Evidence statement

The following statement is supported by the evidence above:

- Re-vegetation of bare peat, along with interventions to aid re-vegetation, can result in increased rates of CO_2 emissions compared with bare peat. (Caporn *et al*, 2007 [1+]); Worrall *et al*, 2011 [2++]). There are no studies that refute this statement.

Impact of re-vegetation on soil microbes

A laboratory comparison of peat from under bare and vegetated areas (Caporn *et al*, 2007 [1+]) found that culturable microbial colonies were observed to be higher in vegetated peat than in bare peat, and levels of basal respiration were higher.

Evidence statement

The following statement is supported by the evidence above:

- Bare peat, following re-vegetation, shows a related increase in the activity and abundance off soil microbes. (Caporn *et al*, 2007 [1+]). There are no studies that refute it.

Impact of re-vegetation on carbon budgets

A comparison of carbon budgets for vegetated, bare and re-vegetated peat in the Peak District (Worrall *et al*, 2011 [2++]) found that indicated that the *Eriophorum* site, and one of the restored sites, were overall carbon sinks, while the dwarf shrub site, and 3 of the re-vegetated sites were carbon sources of a similar magnitude. The bare peat sites were very strong carbon sources around 4-5 times the magnitude of the other sources, and over half of their lost carbon was accounted for by POC losses.

A meta-analysis of carbon and GHG budget studies of peatlands under different managements (Worrall *et al*, 2010 [2+]) concluded that re-vegetation of bare peat would be likely to improve both C and GHG budgets.

Evidence statement

The following statement is supported by the evidence above:

- Re-vegetation of bare peat with grasses and *Calluna vulgaris* will reduce, but will probably not reverse, net loss of carbon from hydrologically unrestored peatlands. (Worrall *et al*, 2011 [2++]); (Worrall *et al*, 2010 [2+]). There are no studies that refute it.

Impact of re-vegetation on erosional peat loss

A comparison of carbon budgets for vegetated, bare and re-vegetated peat in the Peak District (Worrall *et al*, 2011 [2++]) found that POC loss from re-vegetated peatland at most of the sites studied was similar to the intact *Eriophorum* site, at 6-8 tonnes C km^{-2} yr^{-1} compared with 155-206 tonnes C km^{-2} yr^{-1} from the 2 bare sites.

The meta-analysis of C and GHG studies on peatlands (Worrall *et al*, 2010 [2+]) found that both of the 2 studies considered showed reductions in POC loss on re-vegetation of bare peat.

Evidence statement

The following statement is supported by the evidence above:

- Re-vegetation of bare peat results in reduction of POC loss. (Worrall *et al*, 2011 [2++]); (Worrall *et al*, 2010 [2+]). There are no studies that refute it.

Impact of re-vegetation on DOC losses

A study of Re-vegetation of bare peat in the Peak District (Anderson *et al*, 2011b [2-]) found that water colour in the treated catchments either showed a slight increasing trend or no detectable change over time.

A comparison of vegetated, bare and re-vegetated peat in the Peak District (Worrall *et al*, 2011 [2++]) found that DOC flux from bare and re-vegetated sites had similar and overlapping values.

Evidence statement

The following statement is supported by the evidence above:

- Re-vegetation of bare peat with nurse and moorland grasses, and *Calluna* will not reduce DOC loss. (Worrall *et al*, 2011 [2++]) supported by (Anderson *et al*, 2011b [2-]). There are no studies that refute it.

Areas requiring further study

There are two lower-quality studies that report that applying geojute to bare peat encourages more rapid development of cover (Anderson *et al*, 2011b [2-]); (Buckler, 2007 [2-]). While it is not suspected that these results are flawed, further rigorous research, or data from new sources, may also reveal the extent to which geojute application, an expensive intervention, is necessary.

Re-establishment of *Sphagnum*

Suitability of conditions for *Sphagnum* growth in English uplands

A study of the impact of gully blocking in the Peak District (Burtt & Hawke, 2008 [3-]) found that *Sphagnum* mosses colonised areas with locally raised water tables.

A catchment scale monitoring study (Anderson *et al*, 2011a [2-]) noted that grip blocking, grazing reductions and control of burning was followed by increases in *Sphagnum* abundance in a Forest of Bowland catchment.

Various field experiments to reintroduce *Sphagnum* to blanket peat (Hinde *et al*, 2010 [2-]) found that *Sphagnum* established from propagules (beads or strands) survived for at least a year, if not sown in the driest conditions, and seemed to survive best in wetter micro sites with sparse vegetation.

A repeated survey in the Peak District (Caporn *et al*, 2006 [2-]) revisited sites where *Sphagnum* had been introduced or recorded in bog pools the past, and found that over 30 years 4 of the introduced species were present, and 3 frequent, while two additional species were also found, and that *Sphagnum* and bryophytes in general had increased in species richness in the bog pools surveyed, over the last 20 years.

A field survey of 256 sites across the uplands of Northern England (Carroll *et al*, 2009 [2++]) found regional patterns in *Sphagnum* species distribution, with greater abundance, higher cover and more hummock-forming species in the North Pennines, but diversity and cover were also driven by higher water contents and pH values.

Over 40 years ago a survey in the North Pennines (Clymo & Reddaway, 1971 [2+]) noted only 3 species associated with lawns and bog pools, while a more recent and survey in the same area (O'Reilly, 2008 [2++]) found at least seven *Sphagnum* species associated with a range of conditions.

Toxic effects of sulphur pollution on *Sphagnum* observed by Ferguson *et al,* (1978 [1+]) were representative of 1950s conditions of sulphur deposition in the most polluted areas of the pennines, however, the ammonia deposition ranges tested by Sheppard *et al,* (2011 [2++]) may still be experienced in some areas.

A total of 16 field studies considered in this review report the presence of *Sphagnum* on blanket peat in England; in the Peak District (1999, 2000, 2006, 2008, 2009 and 2011), Forest of Bowland (1996, 2009, 2011), Exmoor (2000), Yorkshire Dales (2000, 2008, 2011) and the North Pennines (1971, 1991, 2001, 2008, 2009 and 2010). The species are not always identified.

Evidence statement

The following statement is supported by the evidence above:

- Current atmospheric and climatic conditions in English blanket peatlands are not prohibitive to the growth of *Sphagnum*. A total of 7 studies indicate recent increases in *Sphagnum* abundance or widespread distribution with no climatic or depositional effects: (Carroll *et al*, 2009 [2++]); (Clymo & Reddaway, 1971 [2+]); (O'Reilly, 2008 [2++]) supported by (Burtt & Hawke, 2008 [3-]); (Anderson *et al*, 2011a [2-]); (Hinde *et al*, 2010 [2-]); (Caporn *et al*, 2006 [2-]).

Management to enhance *Sphagnum* survival and growth

A range of *Sphagnum* reintroduction experiments in cut-over peatlands in Canada and in the laboratory (Campeau & Rochefort, 1996 [1++]) found that, for most species, diaspores collected from 0-10cm established best, and most species (except *S. fuscum*) grew best in the laboratory under higher water tables but there was little effect on cover of diaspore size. A field experiment found that plots sown with S. *angustifolium* and *S. fuscum* had better establishment than plots sown with S. *magellanicum* and S. capillifolium with higher-density sowing resulting in better establishment but little influence of fragment length.

An experiment to look at the impact on *Sphagnum* reintroduction of reprofiling and addition of plastic sheets to divert rainfall into low lying areas and locally raise water supply (Bugnon *et al*, 1997 [1+]) found that this treatment increased capitulum density of introducted *Sphagnum* in the lowest parts of the reprofiled areas.

An experiment on the impact of former vegetation type and straw mulch on *Sphagnum* reintroduction success in a cut-over bog in Canada (Boudreau & Rochefort, 1998 [1++]) found that *Sphagnum* established better in the plots formerly vegetated by *Eriophorum*, which were wetter, but responded well to addition of straw mulch to drier areas formerly dominated by dwarf shrubs.

A laboratory experiment examined the effects on *Sphagnum* growth of peat type, water table and fabics to increase shade/humidity (Buttler *et al*, 1998 [1++]) and found that *Sphagnum* plants grown on higher water tables were longer and heavier, while covering mesh increased length by etiolation, and plastic sheeting increased mass. Growth was higher on undisturbed peat with larger pores, but mesh or high water tables helped to increase growth on disturbed peat with finer pores.

A field experiment in a cut-over peatland in Finland (Tuittila *et al*, 2003 [2+]) examined the establishment of *Sphagnum angustifolium* in areas with uncontrolled lower and higher water tables, by placing *Sphagnum* material in shallow cuttings. They found that *Sphagnum* capitula regenerated better than stem material, especially in the drier treatment (water table 35-10 cm below surface), but that establishment was worse in the wetter treatment, which was regularly flooded.

Field surveys and experiments on the impact of Politrichum strictum as a nurse crop for *Sphagnum* re-establishment on a cut over bog in Canada (Groeneveld *et al*, 2007 [1++]) found that *Sphagnum* presence was associated with *P. Strictum*, despite it being associated with intermediate water table and implanting *Sphagnum* under *P. Strictum* carpets or under straw mulch improved its retention of moisture compared to bare peat.

An experiment examining various approaches to *Sphagnum* reintroduction to a Canadian cut over bog (Rochefort *et al*, 1995 [1-]) found that different species regenerated differently from different types of fragments, with some responding better under a high water regime and only *S. nemorosum* did not establish well under any water regime. Fertiliser treatments enhanced *Sphagnum* growth.

Three species of *Sphagnum* were grown individually and in mixtures over different peat substrates in a laboratory experiment (Grosvernier *et al*, 1995 [1++]) and *S. fallax* grew faster than S. *magellanicum* and *S. fuscum* in the mixed-species pots, and in those with higher water tables. More porous peats were associated with higher *S. fallax* growth rate, interacting with water table depth, while more humid microclimates delivered higher growth rates, similar to those delivered by raised water tables.

An experiment examining growth of different species of *Sphagnum* shoots implanted into conspecific *Sphagnum* mats over different peat substrates and water tables (Grosvernier *et al*, 1997 [1++]) found that *Sphagnum* species, then water table and then peat type all significantly influenced *Sphagnum* growth responses. *S. fallax* and S. *magellanicum* grew more at higher water tables and *S. fuscum* was less sensitive to water table, and the response depended on peat type. Peat conditions associated with dry heath vegetation (high Mg:Ca ratio, small particle size, and very low pH) were least conducive to *Sphagnum* growth and while the most condusive conditions were associated with cut-over peat.

An experiment examining the impact of microtopography, companion plants and fertiliser on re-vegetation of cut-over raised bog peatland in Canada (Ferland & Rochefort, 1997 [1++]) found that there was no overall difference caused by microtopography treatments on the establishment of *Sphagnum*, but within plots, establishment was better in hollows than on ridges and flat surfaces. Companion species had no impact on *Sphagnum* capitulum counts, but presence of *Eriophorum angustifolium* treatments increased *Sphagnum* cover (ie. plants were larger), while poorer establishment of dwarf shrubs and mosses probably reduced their impact as companion plants. A larger number of *Sphagnum* capitula were observed in the P-fertilised plots.

The impact on *Sphagnum* re-establishment of *Sphagnum* species, fragment sizes, rates o application, mulches and netting was explored in a series of laboratory and field experiments (Rochefort *et al*, 2003 [1++]). Best regeneration was from *Sphagnum* material collected from 0-10cm, fragments originating less than 6cm below the capitulum, greater densities of application and larger species (with larger fragments). The same collected area of *Sphagnum* fuscum could restore a larger cover of vegetation than for *Sphagnum* magellanicum. Shredded fragments proved less effective as diaspores than non-shredded fragments, and there was comparable recovery in areas spread at colletion: spreading ratios of 1:20 and 1:30 which delivered two thirds of the cover of the 1:10 ratio treatment. Application of straw mulch consistently produced approximately 3-8 times as much cover as unmulched plots. The three mulching/shade treatments applied all increased *Sphagnum* cover over the control with straw mulch also increasing cover of other bryophytes.

The impact of species mixtures and conditions during restoration was explored in a repeated field plot experiment on a cut-over bog in Canada (Chirino *et al*, 2006 [1++]) which found *Sphagnum* recovery rates depended on the climatic conditions with those established in drier growing seasons developing more slowly. Soil moisture was not significant as a covariant predicting the recovery of the *Sphagnum* carpet and hummock species (fuscum and rubellum) produced more cover, compared to lawn species.

Recovery of donor sites used for collecting *Sphagnum* material for restoration was examined by Rochefort & Campeau (2002 [1++]) and they found that, depending on species, collected plots recovered to between 14 and 33% cover after 1 growing season, with no benefit to *Sphagnum* cover recovery in cut plots of adding straw mulch or reintroducing *Sphagnum*. After 5-7 growing season plots showed little difference in community composition from intact bog with some small differences in community composition.

An experiment to implant different sized plugs of different *Sphagnum* species into intact bogs in Ireland and Estonia (Robroek *et al*, 2009 [1+]) found that higher water tables helped to reduce the decline of implanted bog pool *Sphagnum*, but larger plugs of introduced *Sphagnum* helped to maintain or increase cover, especially in more hummock-forming species.

Evidence statement

The following statement is supported by the evidence above:

- *Sphagnum* reintroduction is more successful where water table is raised, humidity is high, and with either shade fabric, nurse vegetation or mulch, and where *Sphagnum* diaspores were collected from the top 10 cm of intact bog, but this depends also on the species used and the physico-chemical conditions of the peat substrate. (Boudreau & Rochefort, 1998 [1++]); (Bugnon *et al*, 1997 [1+]); (Buttler *et al*, 1998 [1++]); (Campeau & Rochefort, 1996 [1++]); (Groeneveld *et al*, 2007 [1++]); (Grosvernier *et al*, 1997 [1++]); (Rochefort *et al*, 1995 [1-]); (Rochefort *et al*, 2003 [1++]) , (Grosvernier *et al*, 1995 [1++]); (Robroek *et al*, 2009 [1+]); (Ferland & Rochefort, 1997 [1++]). There are 2 studies that found contrasting results: one found no relationship between recovering and soil moisture (Chirino *et al*, 2006 [1++]); another found no benefit of straw mulch application (Rochefort & Campeau, 2002 [1++]), and another found higher water tables detrimental due to regular flooding (Tuittila *et al*, 2003 [2+]).

Areas requiring further study

The application of mulches, nurse plants or shade fabric has been demonstrated in the studies above to reduce or counteract the impact of lower water tables to aid *Sphagnum* recovery, in either laboratory experiments on in cut-over Canadian raised bogs. However, no evidence was identified in this review to indicate that the natural recovery of *Sphagnum* or the establishment of newly-planted *Sphagnum* could occur in areas of degraded blanket bog with low water tables, but high humidity, due to mulching, rainfall, nurse crops etc. Given the water retentive properties of both living and dead *Sphagnum* , and difficulties in restoring water tables in severely eroded peatlands, demonstration of this effect on English blanket bogs would be useful to inform practical conservation measures.

A single lower-quality study (Caporn *et al*, 2006 [2-]) indicates that *Sphagnum* reintroductions to upland *Eriophorum* blanket bog can persist unaided for several decades. The long-term prospects for reintroduced *Sphagnum* on English Blanket peatlands would inform its management, but opportunities to study this on long-established reintroduction trials are likely to be scarce. Given the medium-term success of *Sphagnum* reintroductions seen in Canadian cut-over bogs, a lack of knowledge of the long term impacts should not prevent reintroduction programmes for English blanket peatlands, but indicate the importance of establishing accurate monitoring, with controls.

Control of ‘undesirable’ semi-natural vegetation

Reducing the dominance of *Molinia*

A field experiment examined the impact of herbicide, cutting, heather brash and grazing on *Molinia* dominance on a possibly shallow peaty soil (Milligan *et al*, 2004 [1+]) and found that very frequent cutting reduced *Molinia* dominance and increased *Calluna* seedling density, which was also increased during some seasons by herbicide application.

A laboratory experiment explored the effectiveness of different herbicides against *Molinia caerulea* (Milligan *et al*, 1999 [1+]) and found that only three herbicides (glyphosate, quizalofop-ethyl and sethoxydim) produced a sufficient response to calculate ED50 values for *Molinia caerulea*. Only glyphosate reduced *Molinia* root growth to 50% of control levels but this, and some other herbicides tested, also reduced vigour of *Calluna vulgaris*.

A field experiment examined the impact of a range of herbicides on *Molinia* and *Calluna* dominated plots (Milligan *et al*, 2003 [1++])

A field experiment examining the impact of burning, grazing and glyphosate herbicide on *Molinia* dominance on moorland (some deep and shallow peat) in Exmoor, the Peak District and the Yorkshire Dales (Todd *et al*, 2000 [1++]) found that glyphosate, and grazing at some sites, reduced vegetation height, while spring burning either reduced or increased sward height. Burning and grazing reduced litter at some sites, and there were no consistent responses in dry matter yield to treatments. *Molinia* cover was reduced by herbicide throughout, but reductions due to burning did not last past the first year.

A field experiment looked at burning, grazing and litter removal impacts on *Molinia* dominance in the Peak District and the Yorkshire Dales (Marrs *et al*, 2004 [1++]) and found that glyphosate treatment significantly reduced the height and cover of the *Molinia* on where it was a sole dominant throughout the experiment, while other treatments had some significant local effects but no consistent pattern.

A monitoring study of restoration management in the Peak District (Ross, 2011 [2+]) looked at the impacts of a regime of cattle grazing and herbicide on *Molinia* dominance, and found significant reductions in total vegetation cover and *Molinia caerulea* cover from 2006-2008, and significant increases in Campylopus moss from 2006-2010.

Evidence statement

The following statements are supported by the evidence above:

- The dominance of *Molinia caerulea* can be reduced by vigorous cutting, grazing and herbicide treatments. (Milligan *et al*, 2004 [1+]); (Milligan *et al*, 1999 [1+]); (Milligan *et al*, 2003 [1++]); (Todd *et al*, 2000 [1++]); (Marrs *et al*, 2004 [1++]); (Ross, 2011 [2+]). There are no studies that refute it.
- Spring burning does not reduce the dominance of *Molinia*, unless in combination with a more successful approach such as those mentioned above. (Todd *et al*, 2000 [1++]); (Marrs *et al*, 2004 [1++]). There are no studies that refute it.

Areas requiring further study

There were no studies which sought to control the over-dominance of other moorland species. Given the association between *Calluna vulgaris* and piping, DOC, methane and CO_2 emissions, and potential drying impact of this species on blanket peat soils, and its high extent of dominance in blanket peatlands (which represents a cause of floristic degradation), more review or research would be required into how best to control this species, if hydrological, geochemical and biodiversity functions are to be restored.

There were also no studies examining the management of over-dominance by *Eriophorum vaginatum*, which may also exclude positive indicator species and therefore represent floristic degradation. However, presence of this species seems to be associated with loss of fewer functions in peatland, and therefore represent less serious degradation.

Research efforts into control strategies for *Molinia caerulea* are often accompanied by efforts to re-establish *Calluna vulgaris*. None of the studies examined in this review have looked at anything other than vegetation responses, and it would seem appropriate to examine the impact of successful control of *Molinia*, and replacement with Calluna, on the full range of blanket bog hydrological functions. However, it should be noted that some of the research quoted in this review was probably conducted on sites with shallower (<40 cm) peat, and may not represent true blanket peatlands.

Gully blocking

Impact of gully blocking on sediment trapping and re-vegetation

A comparative case study in the Peak District looked at natural re-vegetation of gullied bare blanket peat (Evans *et al*, 2005 [2++]) and found that stone and wood blocks were effective at trapping sediment, encouraging re-vegetation by *Eriophorum angustifolium*.

A before and after study was made of gullies blocked with wooden dams, plastic piling, stones or pine logs (Burtt & Hawke, 2008 [3-]) found that plastic piling dams raised water tables and trapped sediment, which was colonised by *Eriophorum angustifolium*.

Evidence statement

The following statement is supported by the evidence above:

- Blocking gullies with plastic piling dams, stone or wooden barriers trap peat sediment and enable colonisation by plants, particularly *Eriophorum angustifolium*. (Evans *et al*, 2005 [2++]) supported by (Burtt & Hawke, 2008 [3-]). There are no studies that refute it.

Areas requiring further study

This review has found little evidence of the hydrological impacts of gully blocking. Given that the evidence of rapid gully erosion may be biased towards actively eroding sites, and many gullies may not be eroding rapidly (McHugh *et al*, 2000 [2+]) and may be long-established (Mackay & Tallis, 1996 [3-]; Phillips *et al*, 1981 [2+]), further investigation of the impact of gully blocking on the wider functions of peatlands, especially those that are more intact, would help to forestall future problems. A review of how water drains from peatlands, if not through gullies and streams, would be a valuable addition to this.

Grip (drain) blocking

This section identifies evidence considered in this review that addresses the following key question.

Key question: e) Does the blocking of artificial drainage channels (grips)on degraded blanket bog result in a functioning and active blanket bog with abundant peat forming species and representative bog flora and fauna. If so, do all drains require to be blocked?

Impact of grip blocking on wetland plant species

A field experiment in Finland, examining the impact of tree felling and drain blocking on a bog (Komulainen *et al*, 1999a [2+]) found that tree felling and grip blocking increased cover of *Sphagnum balticum*, *S. fuscum* and *Polytrichum strictum, Andromeda polifolia, Vaccinium oxycoccus* and *V. microcarpum*, while *Empetrum nigrum* increased on hummocks, *Cladonia* cover decreased and *Calluna vulgaris* started to die in hollows.

A before and after case study of re-wetted cut-over peatland in Finland (Vasander *et al*, 2003 [2-]) found that abundance of *Eriophorum* increased following re-wetting, over 4 years compared to a control, unblocked site.

A series of repeated surveys on revegetating cut-over peatland in Canada, where water table was raised in part of the area (Lavoie *et al*, 2005 [2+]) found that the re-wetted site increased in cover of *Eriophorum vaginatum*, through larger, less frequent tussocks.

Monitoring of the impact of grip blocking, and other catchment-scale changes in grazing and burning management, in the Forest of Bowland, and other areas (Anderson *et al*, 2011a [2-]) reported an increase in the cover of *Sphagnum*, alongside a temporary increase then a decline in *Calluna* cover.

A case study comparison of drained, intact and drain-blocked blanket peatland in the Yorkshire dates (Holden *et al*, 2011 [2++]) noted that the vegetation differed between the 3 sites (*Molinia* being more common in the blocked site), but this could not be ascribed to the treatment.

Monitoring surveys of peatlands in Exmoor where grips had been blocked (Glendinning, 2012 [2+]) found inconsistent evidence that wetland plant species abundance had increased following blocking.

A comparative survey of vegetation along transects running perpendicular to open grips, and those blocked for 3, 4, 5 and 11 years (Bellamy *et al*, 2012 [2+]) found that the longer-blocked site had lower scores for 'dry' vegetation indicesa and lower indices for bog degradation indices close to the drain. Bog recovery index increased with increased time since blocking for blocked sites, indicating greater prevalence of wetland plants.

Evidence statement

The following statement is supported by the evidence above:

- There is moderate evidence that grip blocking increases the abundance of wetland plant species. (Holden *et al*, 2011 [2++]); (Komulainen *et al*, 1999a [2+]); (Lavoie *et al*, 2005 [2+]); (Glendinning, 2012 [2+]); (Bellamy *et al*, 2012 [2+]) supported by (Anderson *et al*, 2011a [2-]); (Vasander *et al*, 2003 [2-]). There are no studies that refute it, but much of the evidence is either gleaned from general descriptions rather than experimental interventions, poorly-replicated case studies, or could be related to several treatments.

Impact of grip blocking on invertebrates

A survey and study of intact peatlands, gripped and grip-blocked blanket peatland in the North Pennines (Ramchunder *et al*, 2012 [2++]) found that invertebrate abundance and richness was highest in drain-blocked and intact sites and lowest in drained sites.

A case study of a blocked and open grip in North Yorkshire (Phillips, 2008 [2-]) found no significant differences in the Shannon diversity index for invertebrates between the sites based on either the sweep netting or pitfall trapping. More tipulids (presumably larvae) were collected at the blocked site than the gripped site and more chironomids from the open grip site than at the blocked site.

A two year comparative survey of cranefly emergence near blocked and open grips in Wales, the South Pennines and the North York Moors (Carroll *et al*, 2012 [2++]) found that Cranefly abundance increased with soil moisture, with high and low numbers at wetter sites, but only low numbers where dry. This relationship was most prevalent at unblocked drains where there was a higher range of soil moisture values. Soil moisture was higher where drains were blocked, but was lower at the edges of unblocked drains, in the wetter year, and lower 10m away from unblocked than blocked drains in the drier year. In the later year only, with sampling across 3 sites nationally, craneflies were more abundant at blocked drain sites than at unblocked sites.

Evidence statement

The following statement is supported by the evidence above:

- (Ramchunder *et al*, 2012 [2++] & Carroll *et al*, 2012 [2++])) found that grip blocking increases invertebrate abundance and diversity but a further, lower quality, study, found no significant differences in invertebrate communities at blocked and open drains (Phillips, 2008 [2-]).

Impact of grip blocking on water table

A case study of three blocked and three open grips in the Yorkshire Dales (Armstrong *et al*, 2008 [2-]) found that blocked grips were found to have higher water tables than those without blocks, especially downslope, where blocking raised the water table from 12-19 cm to 7-4 cm below the peat surface between 0.5 and 3.5m from the centre of the grip.

An experiment examining clearance of trees and ditch blocking on a bog in Finland (Komulainen *et al*, 1999a [2+]) found that water table was higher in the treated bog (average 20 cm below peat surface).

A before and after case study on the impacts of ditch blocking in cut over bog in Finland (Vasander *et al,* 2003 [2-]) reported increased water table over 4 years, compared to the unblocked site.

A before and after study of the impacts of grip blocking in the North Pennines (Jonczyk *et al*, 2009 [3+]) found that water table remained relatively unresponsive and unchanged on either side of blocked and unblocked grips.

Monitoring of three blocked and three open drains on blanket peat in the Yorkshire dales (Armstrong *et al*, 2010 [2+]) found that water tables around the blocked drains were higher than around the open drains, especially downslope.

A before and after study of grip blocking impacts in blanket peatland in Wales (Wilson *et al*, 2010 [2++]) found that water table became closer to the surface following blocking, at different rates in different areas.

A case study comparison of drained, intact and drain-blocked sites (Holden *et al*, 2011 [2++]) found that mean water table depths were significantly different between the intact, blocked and drained sites (5.8, 8.9 and 11.5cm from the surface, respectively), and water tables were less responsive to storm events in the blocked site, but more responsive than the intact site.

Monitoring of the impacts of grip blocking, and changes to burning and grazing regime in the Forest of Bowland and Peak District (Anderson *et al*, 2011a [2-]) observed that dipwells near blocked grips had have higher water table than unblocked controls.

A comparative survey of the hydrological properties of intact, drained, and drain-blocked blanket peatlands in Yorkshire (Wallage & Holden, 2011 [2+]) found that mean water table was 10.1 cm below the surface in the drained area and 7.3 cm in the blocked area, but 5.8 cm below the surface in intact peatland.

A study of the impact of grip blocking in blanket peat in mid Wales (Wilson *et al*, 2011 [2++]) found that dipwell data was very variable, and no overall trend could be detected.

Evidence statement

The following statement is supported by the evidence above:

- Grip blocking raises the water table but not to the level found in intact peatlands. (Komulainen *et al*, 1999a [2+]); (Holden *et al*, 2011 [2++]); (Wallage & Holden, 2011 [2+]); (Wilson *et al*, 2010 [2++]); (Armstrong *et al*, 2010 [2+]) supported by (Vasander *et al,* 2003 [2-]); (Armstrong *et al*, 2008 [2-]); (Anderson *et al*, 2011a [2-]). However, a further 2 studies found that grip blocking had no detectable impact on water tables (Jonczyk *et al*, 2009 [3+]); (Wilson *et al*, 2011 [2++]).

Impact of grip blocking on flood hydrographs (flashiness)

A before and after study of the impact of grip blocking on blanket peat in Yorkshire (Grayson & Holden, 2012a [2++]) found that grip blocking delayed peak discharge following onset of rainfall and slowed the rate of increase on the rising arm of the hydrograph .

Another before and after study on the impacts of grip blocking in Wales (Wilson *et al*, 2011 [2++]) found overall higher flow rates across all catchments but hydrograph recession rates were generally slower after blocking.

However, an ongoing before and after study (Grayson & Holden, 2012b [2++]) looking at the impact of grip blocking in Yorkshire found little evidence at catchment scale that blocking of grips had yet impacted upon storm hydrographs.

Evidence statement

The following statement is supported by the evidence above:

- There is inconsistent evidence that blocking reduces the flashiness of flood hydrographs. (Grayson & Holden, 2012a [2++]); (Wilson *et al*, 2011 [2++]) recorded lower flashiness in blocked catchments while (Grayson & Holden, 2012b [2++]) found no impact of blocking on hydrograph flashiness.

Impact of grip blocking on water yield (catchment efficiency)

A study examining the properties of intact, drained, and areas with recently or longer-blocked drains (Gibson *et al*, 2009 [2+]) detected a significant difference in water yield, between blocked and open sites, with blocked sites yielding 0.07m3 m^{-2} less than drained ones

A before and after study of grip blocking on Blanket peatland in Yorkshire (Grayson & Holden, 2012a [2++]) found that the amount of discharge resulting from a given amount or intensity of rainfall also appeared to be lower following blocking.

A before and after study of the impact of drain blocking on blanket peatland in Wales (Wilson *et al*, 2010 [2++]) found that average discharge rates were significantly lower after blocking, indicating overall lower yield of water.

Evidence statement

The following statement is supported by the evidence above:

- Grip blocking reduces overall water yield and catchment 'efficiency'. (Gibson *et al*, 2009 [2+]); (Grayson & Holden, 2012a [2++]); (Wilson *et al*, 2010 [2++]). There are no studies that refute it.

Impact of grip blocking on base flows

A before and after study of grip blocking in blanket peatland in Wales(Wilson *et al*, 2011 [2++]) found that drain blocking resulted in more stable and higher flow rates during droughts and slower declines in flow rate during first 5 days of drought periods, in both drains and streams.

Evidence statement

The following statement is supported by the evidence above:

- Grip blocking resulted in more stable and higher flow rates during droughts and slower declines in flow rate during first 5 days of drought periods. (Wilson *et al*, 2011 [2++]). There are no studies that refute this statement.

Impact of grip blocking on peat hydrological properties

A comparison of intact, blocked and drained blanket peat catchments in Yorkshire (Wallage & Holden, 2011 [2+]) found that surface hydraulic conductivity was significantly higher in the blocked areas, than in the drained areas. The blocked areas had a significantly lower bulk density at the surface (0-5cm) than the drained area. This study, however, took no measurements prior to blocking and represented only 3 sites, so pre-existing differences in bulk density cannot be ruled out.

A case study comparison of intact, drained and drain-blocked blanket bog in the Yorkshire Dales (Holden *et al*, 2011 [2++]) found that surface peat bulk density (at 5cm deep) was significantly lower at the blocked site, than the unblocked site.

Evidence statement

The following statement is supported by the evidence above:

- Grip blocking increases surface hydraulic conductivity in peat and reduces surface bulk density. (Wallage & Holden, 2011 [2+]); (Holden *et al*, 2011 [2++]). The study reporting increased hydraulic conductivity (Wallage & Holden, 2011 [2+]) however, took no measurements prior to blocking, and represented only 3 sites, so pre-existing differences in bulk density cannot be ruled out.

Impact of grip blocking on DOC export

A before and after study of grip blocking in blanket bog in Wales (Wilson *et al*, 2011 [2++]) found that flow-weighted loads of DOC showed slight declines after blocking.

Another study of grip blocking impacts on Welsh blanket bog (Wilson *et al*, 2011b [2++]) found that DOC yield declined considerably after blocking.

A comparative and intervention study of intact, drained and drain blocked blanket peatlands in the North Pennines (Gibson *et al*, 2009 [2+]) found that the annual DOC budgets did not consistently show the blocked catchment to have lower DOC than the controls, with the pattern changing from year to year.

A before and after study of grip blocking on two blanket peat catchments in Yorkshire (Grayson & Holden, 2012a [2++]) found that DOC load exported reduced on one site and increased on the other.

Evidence statement

The following statement is supported by the evidence above:

- The evidence relating total DOC export from catchments to blocking suggests variable responses. (Wilson *et al*, 2011 [2++]); (Wilson *et al*, 2011b [2++]) found that blocking grips slightly reduces the DOC export from the catchment: while (Gibson *et al*, 2009 [2+]); (Grayson & Holden, 2012a [2++]) found inconsistent responses (reducing and increasing) among different blocked catchments.

Impact of grip blocking on stream DOC concentrations

Catchment monitoring in the Forest of Bowland and Peak District following grip blocking and changes to burning and grazing regimes (Anderson *et al*, 2011a [2-]) indicated that grip blocking, along with reductions in grazing and burning, was followed by a slight but consistent decline in measured water colour in most of the catchments studied

A national survey of blocked and open drains (Armstrong *et al*, 2008 [2-]) that DOC and water colour (at both wavelengths measured) were significantly lower in blocked flowing drains than blocked or open still drains. DOC was significantly lower in blocked flowing drains than in open drains.

A re-appraisal of this survey data (Armstrong *et al*, 2010 [2+]) found that DOC concentrations in blocked flowing drains was significantly (28%) lower than in open flowing drains

However, a before and after study of grip blocking in the North Pennines (Jonczyk *et al*, 2009 [3+]) indicated no significant difference in colour of water between gripped and blocked, with differences instead related to date of sampling.

A further before and after study on blanket bog grip blocking in Yorkshire (Grayson & Holden, 2012b [2++]) found no impact of grip blocking on DOC concentrations.

A comparison of DOC in drains blocked at different times in the North Pennines (Gibson *et al*, 2009 [2+]) found the highest average stream water DOC concentration was found at the shallow peat site blocked for the longest time, while the catchment with open drains had average DOC concentrations between those of the two recently blocked catchments.

One before and after study of blanket bog grip blocking in Wales (Wilson *et al*, 2011b [2++]) found that DOC concentrations in streams and drains increased slightly.

Another before and after study on grip-blocked Welsh blanket bog (Wilson *et al*, 2011 [2++]) found that DOC concentration during droughts increased significantly after blocking but this variation was not apparent in streams.

Evidence statement

The following statement is supported by the evidence above:

- There is no clear pattern in the response of stream DOC/colour concentrations to grip blocking. (Armstrong *et al*, 2010 [2+]) supported by (Anderson *et al*, 2011a [2-]); (Armstrong *et al*, 2008 [2-]) showed lower DOC in stream/drain waters in blocked compared to openly drained sites. (Jonczyk *et al*, 2009 [3+]; Wilson *et al*, 2011 [2++]; Grayson & Holden, 2012b [2++]) showed no change (Gibson *et al*, 2009 [2+]) showing no change or variable responses and (Wilson *et al*, 2011b [2++]) showed higher DOC concentrations in these situations.

Impact of grip blocking on colour and DOC in soil water

A systematic review of the impacts of drainage and re-wetting on peatland GHG and C dynamics (Bussell *et al*, 2010 [1++]) found that, based on analysis of three studies, with eleven effects, there was overall significant difference in DOC concentrations in soil water between rewetted and drained peatlands.

A comparative study between intact, drained and drain-blocked mires in the Yorkshire dales (Wallage *et al*, 2006 [2+]) found that DOC concentrations in water in drained peat were significantly greater than intact peat and those from Intact peat were significantly greater than those from grip-blocked peat.

Evidence statement

The following statement is supported by the evidence above:

- Grip blocking does not reduce DOC and water colour in soil water. A single study, incorporating 3 studies (Bussell *et al*, 2010 [1++]) supports this statement, while (Wallage *et al*, 2006 [2+]) found reduced DOC in peat soil water in blocked sites.

Impact of grip blocking on POC export

A before and after study of grip blocking on blanket peat in Yorkshire (Grayson & Holden, 2012a [2++]) found weak evidence that POC concentrations were lower following blocking.

Another before and after study of grip blocking in Welsh blanket peatlands (Wilson *et al*, 2011 [2++]) found that blocking led to declines in loads POC exported, but little change in POC concentrations.

A further before and after study of grip blocking impacts on Welsh blanket peatland (Wilson *et al*, 2011b [2++]) found that grip blocking resulted in marked declines in the annual flux of POC.

A case study of ditch blocking and tree felling (Vassander *et al,* 2003 [2-]) reported that suspended sediment and nitrate N were reduced to almost nothing, or halved, respectively, following treatment, but noted a temporary increase in P flux which they ascribed to fertiliser treatments formerly applied to the forest.

However, an ongoing monitoring study of grip blocking impacts in a Yorkshire blanket peatland (Grayson & Holden, 2012b [2++]) could find no indication of significant reductions in suspended sediment since blocking took place.

Evidence statement

The following statement is supported by the evidence above:

- Grip blocking resulted in lower POC export: (Grayson & Holden, 2012a [2++]); (Wilson *et al*, 2011b [2++]); (Wilson *et al*, 2011 [2++]) supported by (Vassander *et al,* 2003 [2-]) while (Grayson & Holden, 2012b [2++]).suggests no significant impact.

Impact of grip blocking on CO_2 emissions

A meta-analysis of the impact of land management on peatland GHG and C flux (Worrall *et al*, 2010 [2+]) found that 7 of 13 studies saw reductions in CO_2 emissions from soil respiration following grip blocking, while 5 showed no change and 1 showed an increase.

One of the studies considered in this meta analysis, on re-wetting and tree felling in a Finnish bog (Komulainen *et al*, 1999a [2+]), found that mean CO_2 rates were significantly lower from rewetted plots compared to untreated plots in one year, and that CO_2 efflux significantly decreased in the hollow-level plots with highest water tables, which were generally significantly lower than in the lawn and hummock level plots over 3 years. Seasonal estimates for CO_2-C balance were positive in rewetted sites (101 g m^{-2}) but near zero in untreated plots. Deep water tables in the untreated plot and the hummock plot increased CO_2 efflux whilst the high water table decreased it in the rewetted plot.

A controlled before and after case study of re-wetted cut-over peatland in Finland (Vasander *et al*, 2003 [2-]) reported that two rewetted areas of peatland either became less of a carbon source or became a sink after 4 years.

Evidence statement

The following statement is supported by the evidence above:

- Grip blocking reduces CO_2 emissions. (Worrall *et al*, 2010 [2+]); (Komulainen *et al*, 1999a [2+]) supported by (Vasander *et al*, 2003 [2-]). However, the second paper is included in the first, which concludes that there is a low probability of improvement in carbon budget on grip blocking. CO_2 emissions are almost as likely to remain unchanged on grip blocking as to reduce.

Impact of grip blocking on methane emissions

A systematic review of the impact of drainage and rewetting on peatland GHG and C dynamics (Bussell *et al*, 2010 [1++]) found five effects measured in 2 studies indicating that rewetted peatlands typically emitted ~16mg CH_4 m^{-2} day^{-1} more than drained ones.

A meta-analysis of the impacts of land management of GHG and C budgets (Worrall *et al*, 2010 [2+]) indicated that drain blocking increased methane emissions, given that 9 out of 9 studies considered showed increased methane emissions following blocking of grips

A controlled before and after case study on a cut-over bog in Finland (Vasander *et al*, 2003 [2-]) found that two rewetted areas of peatland increased methane emissions over 4 years.

A laboratory study examining the impacts of different grip in fills and water tables on peat under different vegetation types on greenhouse gas fluxes (Green *et al*, 2011 [2++]) found that mesocosms representing pools of open water behind grips had the lowest methane emissions compared to those representing grips infilled with heather brash or reprofiled grips, and pools even took up methane from the atmosphere, and that there was no influence of water table (high and static or fluctuating) on methane emissions in these mesocosms. They also found that different plants were associated with significantly different emissions of methane, being lowest in *Sphagnum* papillosum-dominated vegetation and 2-4 times higher under *Calluna* and *Eriophorum*, with *Calluna* emitting more under warmer climates.

Evidence statement

The following statements are supported by the evidence above:

- Grip blocking increases methane emissions. (Bussell *et al*, 2010 [1++]); (Worrall *et al*, 2010 [2+]) supported by Vasander *et al*, 2003 [2-]). However (Green *et al*, 2011 [2++]) suggests that high and constant water tables would not increase CH_4 over more fluctuating ones.
- The type of grip infill used is likely to strongly influences the methane emissions and carbon balance of the grip (Green *et al*, 2011 [2++]) with heather brash infill and reprofiling of grips leading to higher emissions of both CO_2 and methane compare with open water or *Sphagnum* mats. This impact has yet to be proved in the field.

Success of different damming materials

A national survey of blocked and open grips on blanket peatland (Armstrong *et al*, 2008 [2-]) did not present an analysis of the success of damming materials in the report, and (Armstrong *et al*, 2010 [2+]) later reported on the same data that no significant effect of drain block type on block failure in and later reported in that. However, an analysis of the data presented in (Armstrong *et al*, 2008 [2-]) using a Chi-square test indicates that grips blocked with peat dams were less likely to be classed as ‘intact but not redistributing water’ but more likely to be ‘intact and redistributing water’ than dams blocked with other methods (P=0.002, n=275, d.f.= 3).

The same survey was also reported in (Armstrong *et al*, 2009 [2+]) which found that plywood dams and heather bales were least likely to fail, and peat dams just under 60% were class 4 or 5. The study failed to identify the key result that peat dams represented a disproportionately high number of blocks that were in the highest class (intact and redistributing water).

Evidence statement

The following statement is supported by the evidence above:

- Using peat dams to block grips provides comparable or better success rates at retaining water to more expensive solutions. Additional analysis of data presented in support this statement: (Armstrong *et al*, 2010 [2+]); (Armstrong *et al*, 2009 [2+]) and (Armstrong *et al*, 2008 [2-]). However, there are no studies that refute it.

Natural infilling of grips

A field survey of grip properties in blanket peatlands across the Pennines and in Scotland, examining (Holden *et al*, 2007 [2+]) found that drains with slopes under 2o were commonly infilling, and only rarely eroding, while those on 4o slopes or more were most commonly eroding and rarely infilling.

Evidence statement

The following statement is supported by the evidence above:

- Grips on shallow slopes are more likely to infill and re-vegetate and less likely to erode (Holden *et al*, 2007 [2+]). There are no studies that refute it.

Areas requiring further study

The evidence that blocking grips reverses the changes in vegetation seen in blanket bogs following drainage is weak. Much effort has been expended in grip blocking on blanket peatlands that are valued for their biodiversity, and it would be hoped that some of the changes affected would be picked up by detailed monitoring by moorland restoration projects, of SSSIs or of agri-environment schemes. A more directed search is required to establish whether this monitoring data exists, and, if not, detailed vegetation monitoring of blocked and comparative monitoring of unblocked sites should be established as a priority.

This review has indicated that many of the hydrological and geochemical responses of blanket peatlands to grip blocking are hard to predict from our current knowledge, and that there may be other factors at play that exert a greater level of control. It is easy to become confused when interpreting of DOC concentrations in water in soil, grips, stream samples and at catchment outflows and catchments may be very different in size and in the range of influences they reflect. A robust understanding of a range of land management and restoration impacts on hydrology, DOC and POC export would require a widespread programme over several years, and replicated at the catchment scale, with monitoring of other potentially important factors, multivariate statistical approaches, possibly including monitoring on sub-catchments, and replicated application of catchment scale interventions, with comparison to controls.

As an alternative, larger scale (national) correlatory studies of water colour, along with extent of gripping in catchments, extent of grip blocking, extent of other factors (erosion, vegetation, grazing, burning etc.) could be subjected to multivariate analysis. This would require consistent and improvement monitoring of upland vegetation, and acquisition of hydrological data.

In many instances, however, the disagreement in the research is not related to the direction of change, but rather to the significance of it. 'Variable' responses to grip blocking, if treated as true replicates, might either simply indicate no significant change (due to error variability), or may reflect the significant influence of another management. Differences in the results may also relate to the scale of the catchments used in the studies. These results indicate that differences in the catchment flashiness response to grip blocking are very likely to be influenced by local topography.

Data on the impact of grip blocking on CO_2 emissions seems particularly scarce, with the systematic review of Bussell *et al*, (2010 [1++]) having found no qualifying studies, which also calls into question the quality of the studies included in Worrall *et al,* (2010 [2+]).

Are some blanket peatlands unrestorable?

This section identifies evidence considered in this review that addresses the following key question.

Key question: f) are there are conditions where it is not feasible to completely restore a degraded blanket bog to a fully functioning bog system with its representative flora and fauna, and if so what is likely to prevent their full recovery?

There is no evidence in this review to suggest any areas of peat are completely unrestorable.

However, social, political and economic factors may make restoration less desirable. Time scales for full restoration may be prohibitively long. Any environmental situation which falls outside the niche requirements for the plants associated with blanket bog habitats will present difficulties to restoration management, and will need to be ameliorated before management can be successful. However, amelioration of environmental conditions to achieve the correct conditions for establishment and survival of a habitat or community is the mainstay of all habitat restoration management, and does not put damaged peatlands beyond the reach of restoration.

It would be reasonable; perhaps, to assume that bog habitats will not form in areas that rarely, if ever, experience appropriate climatic conditions for bog peat formation. However, the lack of any climate modelling studies in this review means that these limits have not been characterised. There have been attempts to identify the climate ‘envelope’, based on current climate records, that characterises sites where blanket peat is now found (Gallego-Sala *et al*, 2010). However, locations where ombrotrophic peat has formed (including raised bogs) fall outside these envelopes, and the presence of peat influences and may to some extent buffer, the hydrological conditions required to support bog functions. Besides the influence of climate, the persistence of a blanket bog habitat, and the resistance of its functions to adverse climates, is likely to be primarily influenced by hydrology, which is itself influenced by topography, peat condition, management and vegetation, as indicated by this review.

This review has taken, as its scope, the extent of Blanket peatlands, in any state of degradation. However, there is also a possibility that the current location of blanket peatlands may be influenced to some extent by the possibility of gradual peat mass movement, highlighted in this review. It is hard to imagine a situation where hydrological conditions could be maintained to develop deep peat deposits where they are found at the steepening edges of hill slopes, or where haggs are found on these slopes themselves. In these situations, there is a possibility that the peat mass has moved, either gradually or rapidly, to leave these deposits here, where their erosion and loss would seem inevitable. These areas may represent unrestorable blanket peat, but loss here would be counteracted by restoration on higher, flatter ground. More research is needed, however, to demonstrate whether this is indeed the case.

It is also possible that the topographic or hydrological conditions that were present at the onset of blanket peatland formation are no longer present, and would represent insurmountable difficulties to restore (for example, due to landslips). Less extreme examples might include quarrying, development of infrastructure or buildings, although none of these completely preclude restoration.

What are the wider impacts of restoration?

This section identifies evidence considered in this review that addresses the following key question.

Key question: g) Are there any wider environmental impacts resulting from the restoration of degraded blanket bogs?

Because our definition of degradation was a loss of peatland function, many of the wider impacts of restoration have been considered in the sections above. Others, relating to economic, cultural, social or relating to food production are outside the scope of this review. Numerous Evidence statements have already been provided indicating the wider impacts of restoration, and will not be repeated here.

The issue of different management and activities on blanket peatland GHG flux has been considered throughout this review, with the evidence largely drawn from a systematic review, (Bussell *et al*, 2010 [1++]) and a meta-analysis (Worrall *et al*, 2010 [2+]). These provide an overall picture of intact blanket peatland being a net carbon sink but a net source of greenhouse gases due to methane emissions. Emissions of methane are reduced following managements that lower the peat water table (such as drainage or afforestation), but this is accompanied by increases in carbon dioxide emissions. However, the greenhouse gas impact of drainage may be beneficial overall, but may also increase losses through non-gaseous routes (DOC, POC) and the fate of carbon lost by these routes is not clear. Deforestation stops the rapid carbon capture by trees, but will also help to prevent the ongoing loss of peat C, provided bogs can be restored, but is unlikely to result in short term C benefits. Re-vegetation of bare peat will result in carbon benefits over the bare peat, especially reducing POC losses, but may not stop ongoing loss of DOC from the peat (Worrall *et al*, 2011 [2++]), following the initial capture of atmospheric C by the new vegetation. Re-wetting a peatland may help to prevent C loss as CO^2 from the peat, but will increase methane emissions, at least over the short term, but increased emissions may be amenable to control through management of the vegetation (Green *et al*, 2011 [2++]).

Appendix 6 Evidence table

A Microsoft Excel version of the Evidence table is available on Natural England's publication website.

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