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The impacts of tracks on the integrity and hydrological function of blanket peat (NEER002)

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Natural England Evidence Review NEER002

The impacts of tracks on the integrity and hydrological function of blanket peat

Mike Grace[1], Alan Dykes[2], Simon Thorp[3] and Alistair Crowle[1]

[1]Natural England
[2]Kingston University
[3]Heather Trust

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Contact details

Mike Grace
Principal Specialist
Natural England
Telford - Parkside Court
Hall Park Way
Town Centre
Telford
TF3 4LR
mike.grace@naturalengland.org.uk

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Cover photograph

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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

In recent years, in the English uplands, there has been an increase in the number of requests to construct tracks upon blanket bog for example to facilitate grouse management. In addition to this, there has also been an increase in the use of all-terrain vehicles in the uplands associated with upland management in general. Aside from the visual intrusion on the landscape there are concerns that the use of made and unmade tracks has effects on the processes and structure of blanket peat and are associated with major events such as landslips, as well as more subtle changes that disrupt the active formation of peat. Blanket bog is a globally rare habitat and much of its area receives protection under domestic and European legislation. In order to be able to ensure these sites receive the appropriate protection it is essential that we understand the impacts of track construction and vehicle use.

Purpose and focus of the review

This report covers one of five topics that form the Upland Evidence Review Programme being conducted by Natural England. All five topics have been addressed concurrently and this topic review forms part of the overall programme report.

The original over-arching question for this topic review was:

What are the impacts of tracks on the integrity and hydrological function of blanket peat?

Impacts on biodiversity were included within the scope of this topic review, but other than the loss of surface vegetation, no evidence was found that related to this issue so it is not considered further in this report.

This topic review report therefore addresses the available evidence to help understand the impacts of tracks and vehicle use on the structure and hydrology of blanket peat. Four sub-questions provided further focus for the topic review and these addressed **the structural integrity of peat, hydrological issues, vehicle usage** and **erosion issues**. The sub-questions were outlined in the draft scope of the Review Programme and refined following stakeholder feedback to address the key concerns.

This topic review is confined to a consideration of available information and this is used to identify some knowledge gaps. The topic review does not consider the effect of the state of our knowledge on Natural England's policy and advice; this will be a separate phase of work to follow the Upland Evidence Review Programme.

Process used in reviewing evidence

The initial search of the available evidence produced a list of 754 relevant papers and these were further filtered to identify 106 papers that were directly relevant to the review questions. In turn these were assessed against inclusion-exclusion criteria and evaluated closely. As a result of this process, 49 papers were accepted for quality assessment and data extraction with a further 5 being considered to be of relevance to the topic review although not providing quantifiable evidence.

A topic review group [the authors of this report] was established to agree the interpretation of evidence and from this; the group drew the conclusions that are found in each of the relevant sections. These conclusions were then used to determine a number of recommendations for further research.

Conclusions on the impacts of tracks and vehicle use upon the structure and hydrology of blanket peat

The topic review group has been careful to be led by the evidence and from our consideration of the evidence in which we had confidence we were able to reach a conclusion in respect of all of the sub-questions posed. The lack of evidence addressing the ecological impacts of tracks (aside from impacts upon vegetation) meant that we could not draw any conclusions in that respect.

In answering the over-arching topic review question, *what are the impacts of tracks upon the integrity and function of blanket peat*, it is that tracks have a number of impacts on the structure and hydrology of blanket peat. Constructed tracks affect structural integrity and can cause instability. The hydrology of peat is affected by construction, and drainage through ditches that can further affect stability. As might be expected the type of vehicle, loading and usage influences the impact of unmade tracks and there is evidence to suggest that in these cases erosion can become an ongoing problem.

More particularly, we have been able to reach the following conclusions:

- Tracks alter the structural integrity of blanket peat. Building upon peat compresses the peat and alters the drainage patterns on and around the peat, both within the peat body and over its surface. The level of compression and disruption depends upon the structure and wetness of the peat in question.
  Peat that is loaded (for example, by being built on) will consolidate, the permeability will reduce (affecting natural sub-surface drainage) and the level of surfaces and any structures will settle. Drier peat has a stronger surface layer than very wet or saturated peat, and therefore tracks on dry peat are less likely to cause damage. Drainage ditches can feed or focus water into areas of weak peat, thereby potentially creating instability. Similarly, the cutting of drainage ditches across slopes removes support for the slope above and damages the structural integrity of the peat deposit. This may also lead to instability.
- Tracks alter the hydrological system of blanket peat at either surface or sub-surface level. The artificial drainage of peat results in the settlement of the peat, which disrupts the hydrology both within the sub-surface peat body and over its surface. Drainage channels are damaging as they result in drying of the peat and may lead to instability of the peat depending upon their position within the slope or by channelling water into areas of structural weakness.
  Constructed tracks result in the settlement of peat and the reduction of sub-surface flow through the peat because of the consolidation process. Compression of the peat through track construction may lead to accumulations of surface runoff water (ponding), which may lead to erosion and/or instability of the track and adjacent peat. Constructed tracks usually require ditches to be made to manage runoff, but these ditches are normally damaging because they result in drying and possibly instability of the peat. Drainage of peat results in deformation (in the form of settlement) of the peat.

- The type of vehicle, loading and usage influences the impact of unmade tracks upon the structural integrity and hydrology of the blanket peat. Vehicle use on unmade tracks is damaging to the surface vegetation. The level of damage depends upon the type of & weight of the vehicle, the number of journeys made and the type and wetness of the peat in question.
  The number of vehicle movements, the weight and the type of tyre or 'caterpillar' track used by the vehicle are relevant, with weak evidence to indicate that rubber 'caterpillar' tracks may reduce the level of impact. One study showed that vehicle use on unmade tracks damages vegetation in ways that may be irreversible. We found that the evidence is insufficient for any meaningful comparisons to be made relating to the impacts of vehicles moving across constructed tracks.
- The disruption of blanket peat by tracks (both constructed and unmade) at surface and sub-surface level results in erosion and this erosion is ongoing. The science does not allow the separation and quantification of this erosion. From the available evidence we have not been able to quantify levels of erosion derived from a constructed track as there is no research that has addressed this subject in isolation.

Research recommendations

Finally, the report sets out a number of concluding remarks and recommendations that are suggested by the evidence, which we hope will be of interest for the direction of future research and operational considerations. Including investigations of:

- The reduction of permeability that results from consolidation at surface and sub-surface levels under a 'floating' constructed track by means of long-term monitoring of a track (or tracks) following construction and with reference to pre-construction conditions.
- The biodiversity impacts arising from (a) altered downslope hydrological conditions and (b) the use of alkaline road gravel (limestone) on otherwise acidic peatland.
- Other relevant hydrological properties of the peat mass including features such as pipes and desiccation cracks, and how they may affect the overall response of the peat.
- The geotechnical properties of the peat mass, how they relate to the botanical composition of the peat and how they change under loading.
- Surficial hydrology, erosion and vegetation change at a variety of contrasting sites damaged by temporary constructed tracks.
- Surface and subsurface peat properties and conditions following disturbance by vehicles driving across the peat and with reference to pre-construction conditions.

Contents

Appendices

List of tables

List of figures

List of plates

Appendix 3:

1 Introduction

Background

1.1 In March 2011 Defra published the Government's review of uplands policy which sets out a range of actions the Government will take, led by Defra and 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 to 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[1] 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 contribute to a range of ecosystem services although this topic review (tracks) does not investigate these 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 Uplands Evidence Review Programme seeks to draw together the best available evidence to provide sound evidence of the effects of land management activities on upland

[1] Ecosystem services can be defined as services provided by the natural environment that benefit people. These benefits include:

- Resources for basic survival, such as clean air and water;
- A contribution to good physical and mental health, for example through access to green spaces, both urban and rural, and genetic resources for medicines;
- Protection from hazards, through the regulation of our climate and water cycle;
- Support for a strong and healthy economy, through raw materials for industry and agriculture, or through tourism and recreation; and
- Social, cultural and educational benefits, and wellbeing and inspiration from interaction with nature.

For further information see: **www.defra.gov.uk/environment/policy/natural-environ/documents/nature-do-for-you.pdf** biodiversity and ecosystem services. In doing so, it provides a basis for advice and decisions on future management of the uplands.

1.7 In recent years, in the English uplands, there has been an increase in the number of requests to construct tracks upon blanket bog to facilitate grouse management. In addition to this, there has also been an increase in the use of all-terrain vehicles in the uplands associated with upland management in general. Blanket bog is a globally rare habitat and much of its area receives protection under domestic and European legislation. In order to be able to ensure these sites receive the appropriate protection it is essential that an understanding of the impacts of track construction and vehicle use is established.

The nature of the evidence

1.8 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 the relevant literature, notably the lack of consistency between measurement methods and different outcomes measures, overall the results provide a basis from which conclusions about intervention effects and research needs can be developed. The focus of most of this work has been upon vegetation and species and their interaction with land management practices. Little or no research has been carried out into the impacts of interventions involving the construction of tracks or buildings.

1.9 It is worth noting a number of significant challenges associated with undertaking a review of the evidence relating to upland management interventions. Firstly, the search strategy needs to be broad enough to capture studies from non-traditional sources including journals and other works not indexed in environmental databases, and work that may be in the 'grey' literature (such as 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-intervention only measures' or 'uncontrolled pre- and post-intervention studies', increasing the risk of bias.

Overall scope of the Upland Evidence Review Programme

1.10 The uplands are a broad biotope encompassing a variety of habitat, species and ecosystem services, and are subject to a variety of land management interventions. This review will focus on five issues where there are significant challenges:

- The impacts of tracks on the integrity and hydrological function of blanket peat.
- Restoration of degraded blanket bog.
- The effects 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.

1.11 This report presents the findings from the 'impacts of tracks' topic review.

1.12 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. Climate scenarios are also excluded from the topic review.

Review topic: Impact of upland tracks

Blanket bog development and structure and why there is a conflict with track development

1.13 Blanket bogs accumulate when decaying plant remains are maintained in a saturated condition by rainfall, in climates where the annual rainfall exceeds the annual evapotranspiration.

1.14 In many cases two distinct layers can be identified within a blanket bog. The upper layer is known as the 'acrotelm' and comprises a strong, fibrous mat of living vegetation and live roots, over the upper layer partially decomposed plant remains. Beneath the acrotelm is the 'catotelm', in which the humification (degree of decomposition of plant remains) increases and permeability typically reduces with depth as the fibre content reduces and the proportion of amorphous matter increases. The catotelm material is weaker than the acrotelm and it may contain sub-surface structures such as natural pipes or relict, desiccation cracks that act as conduits for rapid subsurface drainage of rainwater.

1.15 These attributes of blanket bog are significant because there are an increasing number of constructed tracks on blanket peat to enable vehicular access for a range of land management operations. These are relatively linear features in the landscape that may change the peat structure and alter the nutrient and hydrological environment, affecting the ecosystem services and biodiversity of blanket peat.

What is considered in this topic review?

1.16 The evidence in this topic review covers the creation of vehicle tracks across blanket peat, including both constructed and 'unmade' (ie no surface preparation or protection) routes. The primary focus is on constructed tracks that require hard engineering, but the review will also consider the use and impact of mesh products that provide less intrusive alternatives to constructed tracks. No studies were found that investigated the impacts of tracks or vehicles upon the wider biodiversity of blanket peat or upon associated ecosystem services. This topic review did not produce any evidence statements based upon any cost-effectiveness data.

The over-arching topic review question

1.17 **What are the impacts of tracks upon the integrity and function of blanket peat?**

The following sub-questions were the focus of the topic review:

a) Do tracks (constructed or unmade) alter the structural integrity of blanket peat?
b) Do tracks (constructed or unmade) alter the hydrological system of blanket peat at either surface or sub-surface levels?
c) Does the type of vehicle and usage influence the impact of unmade tracks on either the structural integrity or hydrology of the blanket peat?
d) Do tracks lead to enhanced erosion of blanket peat?

1.18 The sub-questions were drawn up to try and address the commonly perceived issues relating to vehicle and track use on blanket peat. Historically, these have focused upon hydrological and structural changes to the blanket peat as a result of activities associated with vehicular access.

1.19 Chapter 2 of this report briefly describes the methods and process for this topic review. Chapters 3 to 6 consider the four sub-questions in turn. These chapters provide a short summary of the evidence, underpinned by a more detailed analysis of the evidence which is used to derive evidence statements, which encapsulate the nature and strength of the evidence. Conclusions are reached about the effects of tracks based upon the evidence reviewed and recommendations for further research are suggested where gaps in the evidence are identified. Chapter 7 provides a summary and concluding remarks and chapter 8 draws together the research recommendations.

Comparator

1.20 The comparators for the questions in this topic review are either:

1) Functionality[2] of blanket peat prior to intervention; or
2) Functionality of blanket peat where intervention has not occurred.

[2] Functionality in this case means the ability of the peat to behave naturally, i.e. natural hydrological flows are maintained and peat forming plants occur and are setting down peat.

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). Duplicate references were removed. References were also identified through direct contacts with key international and national experts and lead organisations. In addition, there was an open call to interested stakeholders to submit documented evidence for consideration as part of the review and 8 submissions were received.

Search terms

2.3 The following search terms were used:

Blanket peat, Blanket bog, Blanket mire, Peat, Bog, Mire, Peatland, Peat soil, Soil, Upland, Track, Road, Route, Vehicle, Machinery, Traffic, Access, Floating road, Construction, Building, Engineering, Damage, Degrade, Compaction, Compression, Impact, Erosion, Sediment, Carbon, Particulate, Hydrology, Drainage, De-watering, Biodiversity, Vegetation change.

Search strategy

2.4 The following databases were searched:

Web of Science (from 1990), CAB Abstracts (from 1990), Zoological Record (from 1978), Olib, Scirus, IngentaConnect, Google Scholar, Google, NORA, ScienceDirect (Engineering subject collection), Transport Research International Documentation (TRID).

2.5 Publication searches were undertaken on:

British Library ETHoS, the CCW library catalogue and EPA Ireland.

Selection of studies for inclusion

2.6 The search strategy resulted in 754 titles. These were screened by title and abstract for relevance. In total 106 were assessed as likely to be relevant and the full papers were retrieved, checked against the inclusion-exclusion[3] criteria and evaluated closely. Where any uncertainty existed, the full paper was assessed by a second reviewer. Having put the 106 publications through this process, 54 remained and were accepted for quality assessment and data extraction.

[3] Publications relating to the construction of major highways over peat were excluded unless they included studies of peat responses to loading. One paper was excluded on this basis. Studies focused upon peat structure in permafrost environments were also excluded (2 papers) but studies that related to bog vegetation on semi-permafrost sites were not.

Table 1 Number of sources examined for this review

Review stage	Number of studies
Studies captured using search terms in all sources (excluding duplicates)	754
Studies remaining after title filter	568
Studies remaining after abstract filter	356
Studies remaining after full text filter	106
Studies used in review	54

A list of the references will be available on-line.

Study type and quality appraisal

2.7 Each study was categorised by study type (Table 2), then quality-appraised against criteria appropriate for each study type and given one of three quality ratings (Table 3). This approach followed that set out in the project brief.

Table 2 Types of studies

Rating	Definition
1	Meta-analyses, randomised control trials (RCTs) (including cluster RCTs) or systematic reviews of RCTs.
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.
3	Non-analytical studies, for example, case reports, case series studies.
4	Expert opinion, formal consensus.

Table 3 Quality categories of studies

Rating	Definition
++	All or most of the methodological criteria, as set out in the assessment forms, 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).

2.8 Table 4 provides a summary of the study types and categories. A full listing of papers is in Annex 1. No Type 1 studies were found. The main reasons for studies being assessed as '–' quality were (i) failure to describe methods adequately, (ii) a low quality measure of ecosystem and biodiversity outcomes, and (iii) failure to take potential confounders[4] into account. No studies with a '-' score were considered within the tracks topic review.

Table 4 Summary of study quality and type

Study type and quality rating	Number of studies
2++	23
2+	20
3+	1
4+	10

Study categorisation

Description of studies

2.9 Forty-nine (49) studies are described in sections presenting the summary of findings (Section 3) and in the Evidence Table. Five of the final 54 publications/submissions did not provide quantifiable evidence, but were recognised as being of relevance to this review: Countryside Commission for Scotland (1978), Land Use Consultants (2005), MacCulloch (2006), Stoneman (1997) and United Utilities (2012). The issues raised in these submissions/reports will be discussed in Section 7 of this report. The 49 studies include:

- 3 'before-and-after' studies; and
- 6 'controlled before-and-after'.

2.10 These studies tested a range of different environmental interventions related to the effects of tracks on the integrity and function of blanket peat (but not did investigate the impacts in relation to the ecosystem services provided by blanket peat). They were assessed under 4 different categories:

- structural integrity of peat;
- hydrology of blanket peat;
- vehicle use; and
- erosion of blanket peat.

Study locations

2.11 Sixteen of the credible studies were conducted in Great Britain. Table 5 presents the frequency of studies by country.

[4] Confounders are things that may have an effect upon the results obtained and ideally need to be eliminated in the experimental design. Where this has not been possible, they need to be considered when drawing up conclusions.

Table 5 Summary of studies by country of origin

Country or region of origin	Number of studies
Great Britain	16
Ireland*	14
North America	11
Russia	1
Sumatra	1
Finland	3
Italy	1
Scandinavia	1
Malaysia	1

*In this report, 'Ireland' refers to the geographical island of Ireland, comprising Northern Ireland and the Republic of Ireland

Duration of outcome measures

2.12 Five studies measured a combination of short- and long-term measures (Barden 1968, Lake 1961, Ahlstrand 1993, Blackwood 2006, Fox 1996, Alakukku 1996a & b, Ruseckas 1998). All of the remaining studies were of less than 12 months' duration.

Strength of evidence

2.13 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. A study may for example have a very high quality score based on the design and analysis, and the findings in relation to the effects of tracks may be important, but the aims of the study may be wider and cover a range of treatments.

2.14 Unusually perhaps, the studies assessed within this topic review were largely saying the same things. There was not one study which reported findings that were at odds with all the others.

2.15 The strength of evidence is defined as follows:

- **Strong** - was used where there is a large number of studies that are in agreement (>5).
- **Moderate** - was used where there is a smaller number (3-5) of studies that are in agreement.
- **Weak** - was used where there is only one or maybe two studies involved.

Assessing applicability

2.16 Each study was assessed in terms of its external validity: that is, whether or not it was directly applicable to the scope of the Review. This assessment took into account the location of each study and any reasons why a study might not be relevant or valid for the Review. Several issues were identified that were not taken further, such as metalled roads, and we did not find any evidence of the influence of animals in terms of track development or use. This left five issues to be considered:

a) timescale;
b) type of track;
c) theoretical relationships between impacts of track construction on different properties and characteristics of the peatland and its constituent peat material;
d) vehicles driving directly on the peat; and
e) structural integrity of the peat and what this means.

Issues that were taken into account

Timescale

- Immediate impacts associated with construction of the track.
- Short to medium term impacts of the track existing and being used.
- Residual impacts following removal of a temporary track.
- Long term impacts of the continuing existence of the track.

Type of track

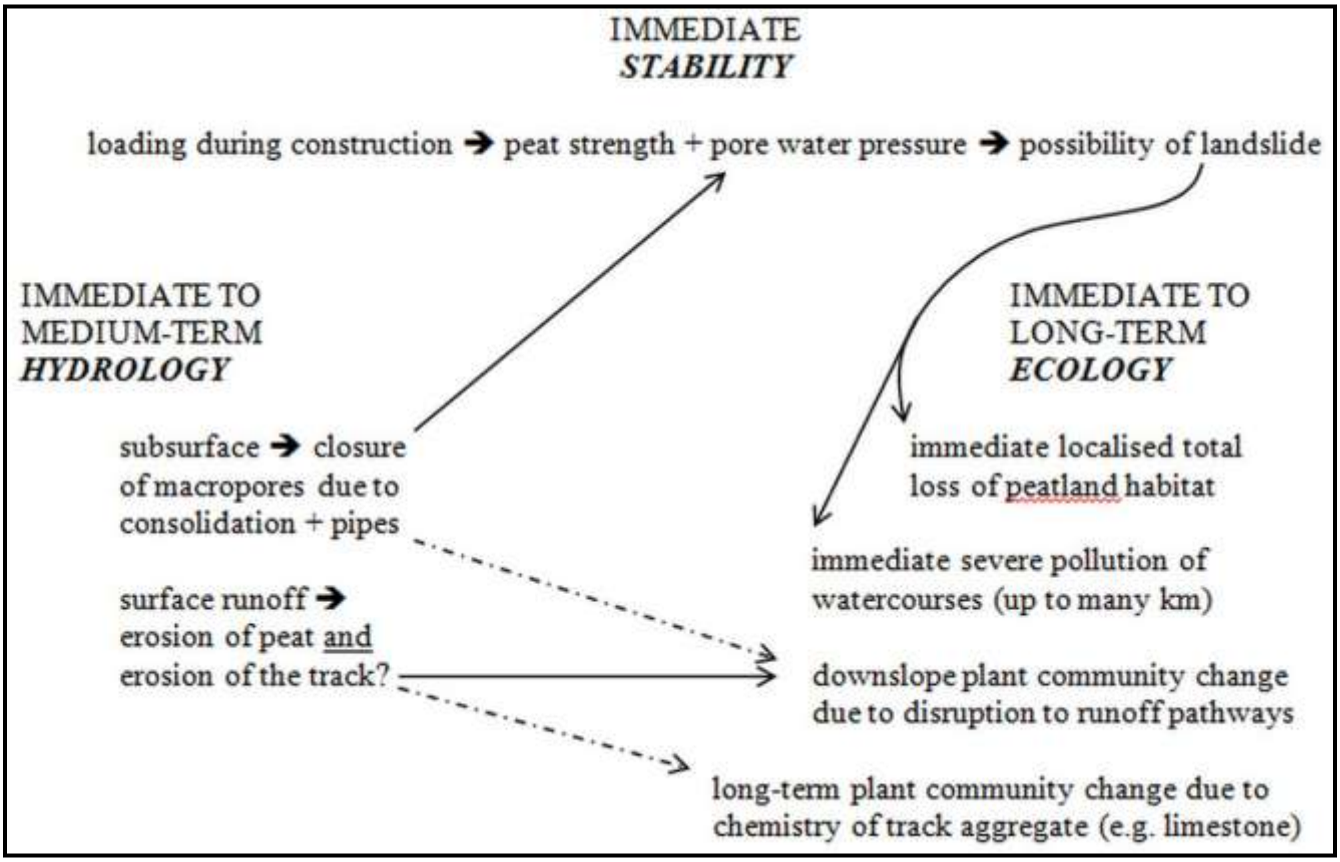
- Unmade tracks and footpaths.
- Constructed tracks:

1) Small, temporary track – lightweight surface geotextile membrane only.
2) Small, 'permanent' track – 'floating' track comprising thin layer of aggregate placed on a geotextile membrane.
3) Heavy-duty 'floating' track (for example, for wind farm construction) – as above but wider, with a thicker gravel layer and possibly an additional layer under the geotextile (for example, tree trunks).
4) Heavy duty track (for example, for forestry) formed on the mineral surface having excavated the peat.

2.17 The evidence and conclusions were considered in the context of the distinction between track types.

2.18 The type of track, and therefore the nature and extent of the immediate impacts associated with construction, will depend on the purpose for which it is planned, except that 3) and 4) are alternatives for the same purpose, usually depending on the depth of peat and slope gradient. It will also depend on the likely usage in terms of size (dimensions, total weight, contact pressures) of vehicles and the frequency of vehicle movements along the road.

Theoretical relationships between impacts of track construction on different properties and characteristics of the peatland and its constituent peat material



(Diagram: A P Dykes). Solid long arrow = major effect of one impact on another; dashed long arrow = minor effect; arrows indicate the direction of influence.

Figure 1 Conceptual framework for understanding the linkages between different impacts of track construction

2.19 The scientific studies of peat can be categorised under three very broad headings: (i) ecology (including biodiversity and palaeoecology), (ii) hydrology, and (iii) geotechnics (particularly relating to stability). Under each of these headings there may be several distinct impacts of track construction, and these are likely to take effect over different timescales relative to the time of track construction. Furthermore, some of the distinct physical impacts may directly influence, or even give rise to, other effects under the same heading or other types of impacts under other headings. Figure 1 shows how some of the main types of impacts relate to each other. Track construction will cause consolidation of the peat and may cause the immediate closure of subsurface pipes and macropores, both of which will increase the pore water pressures in the peat and, in turn, may trigger a landslide in certain circumstances. On the other hand, immediate or progressive hydrological change (either impact) may be expected to give rise to some kinds of ecological (including biodiversity) changes over longer periods of time. If a landslide occurs, there will be immediate and potentially major ecological impacts. Note that the 'stability' impacts necessarily follow each other in the sequence shown but may not actually result in a landslide. The 'hydrology' impacts are independent of each other, as are the 'ecology' impacts.

Vehicles driving directly on the peat surface

- Size of vehicle (total weight, contact pressure - thin tyres v wide tyres v tracks?).
- Frequency of movement over the same patch of ground.

2.20 The same factors relate to people walking on peat, ie how often a person steps on the same bit of peat and the type of footwear they are using. Researchers have found that on some sites a single footprint is identifiable a year after it was made.

The structural integrity of peat

2.21 Sub-question 1) considers 'structural integrity' of the peat. This is taken this to mean any disruption to the physical continuity of the peat mass that may give rise to structural weakness (including landslides) or expose the surface peat to erosion. However, it could also include the compression/consolidation of peat under the load of a 'floating road', particularly if significant subsurface structures such as natural pipes become closed as a result, but in any case because the physical properties of the peat mass are being altered.

Synthesis

2.22 It was not appropriate to use meta-analyses (techniques for contrasting and combining different studies) to synthesise the outcome data because the interventions (the types of experiment/investigations), methods and outcomes were heterogeneous (diverse). This review is restricted to a narrative overview of all studies that met the inclusion criteria and contained sufficient information for data extraction and quality assessment. The studies were examined with respect to the scope identified by the 'impact of tracks' sub-questions and stratified by study quality. The evidence statements were developed using:

- 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.

Both photos: A P Dykes (16 September 2008).

Figures 2 and 3 On 22 August 2008, work to construct a 'floating road' on 3 m deep blanket peat, to provide access for a new wind farm on Ballincollig Hill, Co. Kerry, Republic of Ireland, triggered a 130,000 m^3 landslide (see paragraph 3.30 for evidence statement). Peat- cutting activities 10 years earlier constituted a contributory factor in this event. The photos show the site after about 100 m of destroyed road had been rebuilt into the landslide area in order to facilitate recovery of the construction plant

3 Do tracks (constructed or unmade) alter the structural integrity of blanket peat?

3.1 The chapter explains key terms, summarizes the nature and strength of the evidence and identifies the conclusions reached based upon the evidence reviewed and recommendations for research in relation to this question.

3.2 The ‘structural integrity of blanket peat’ refers to the overall state of the physical structure and corresponding physical, hydrological and geotechnical (‘mechanical’) properties of the entire peat deposit. The structural integrity can be altered in two main ways:

1) Cutting or excavation of the peat (which includes the creation of ditches), which creates weaknesses in the overall peat deposit on the slope by breaching the structural (particularly acrotelm strength) continuity and/or removing support for the entire thickness of peat upslope of the cut.
2) Loading of the peat by placing materials such as gravel fill for a ‘floating’ road, which vertically compresses the peat (a process known as ‘consolidation’) and may cause adverse changes in water pressures between individual microscopic particles of the peat, which may reduce the intact strength of the catotelm material. The natural subsurface drainage conduits (ie pipes and other macropores) may also become closed, leading to localised high water pressures and increased surface runoff further upslope. Consolidation of the peat under such loading necessarily results in lowering of the elevation of the original peat surface and, therefore, of anything placed on it.

Summary of evidence and conclusions

3.3 There are one 2++, five 2+, two 4+ publications regarding tracks/roads that are relevant to this evidence question and three 2++ publications that refer to vehicle movements. In addition there were ten 2++, thirteen 2+, two 4+ publications assessed as being relevant to this evidence question.

3.4 There is strong evidence that loading (building upon) of peat results in the settlement (compression) of the peat (Barden, 1968 [2+], Berry, 1983 [2+], Hobbs, 1986 [2++], Blackwood *et al.* 2006 [2+],Munro, 2004 [4+], Fox & Edil, 1996 [2+], Lefebvre, 1984 [2++], Hanrahan, 1964, [2+], Lake, 1961 [2+], Gunn, 1998 [4+], Landva & Rochelle 1983 [2+]).

3.5 There is moderate evidence that compression of peat reduces the permeability of the peat (Berry *et al*. 1975 [2+], Hobbs, 1986, [2++], Mesri & Ajlouni, 2007 [2+]).

3.6 There is weak evidence that vehicle use over thin peat results in compression of the peat/soil layer (Alakukku 1996a & 1996b [2++, 2++]).

3.7 There is moderate evidence that drainage of the peat results in settlement (Barry *et al*. 1992 [2+], Hobbs, 1986 [2++], Bradof, 1992 [2++], Rahman *et al*. 2004 [2++]).

3.8 From this, we conclude that:

- If peat is loaded (for example, by being built on) it will consolidate, the permeability will reduce (affecting natural sub-surface drainage) and the level of surfaces and any structures will settle.

3.9 There is strong evidence that drainage ditches may be a factor linked to peat slope instability (Dykes *et al*. 2008 [2++], Yang & Dykes, 2006 [2++], Dykes & Kirk, 2006 [2++], Dykes & Kirk, 2001 [2++], Carling, 1986 [2+], Tomlinson & Gardiner, 1982 [2+], Wilson & Hegarty, 1993 [2+]).

3.10 There is weak evidence that tracks have been the cause of peat failures (Dykes & Jennings, 2011 [2++], Lindsay & Bragg 2005 [4+]).

3.11 There is weak evidence that the initial draining of the surface of peat can lead to an increase in tensile strength (Casagrande, 1966 [2+], Rahman *et al*. 2004 [2++]) and so could provide an increased resistance to the erosive effect of vehicle tyres/tracks or footsteps.

3.12 From this we conclude that:

- Drier peat has a stronger surface layer than very wet or saturated peat, and therefore tracks on dry peat are less likely to cause damage.
- Drainage ditches can feed or focus water into areas of weak peat, thereby potentially creating instability.
- The cutting of drainage ditches across slopes may damage the structural integrity by removing support for the slope above and damages the structural integrity of the peat deposit. This may also lead to instability.
- Due to the large number of studies in this section they are presented under three headings: Consolidation, Peat Stability and Vehicle Use.

Analysis and evidence statements

Consolidation (settlement) of peat

3.13 One study (2+) that proposed a simplified model for predicting primary and secondary consolidation of clay and peat reported that their results agreed with others in that drainage results in deformation of the peat, but that the processes taking place were not necessarily agreed (Barden, 1968). This author also recognized that that drainage of micro-pores was a key process but at the time of writing, the physics was not yet established.

3.14 One study (2+) identified that lowering of the water table was expected to cause settlement of the peat by three mechanisms: (i) increase in (vertical) stress causing rapid settlement in permeable peat; (ii) shrinkage of the peat as it dries due to the lost water having occupied a large proportion of the peat volume (iii) allowing aerobic conditions that result in an increased rate of decomposition (Barry *et al*., 1992). These authors reported that field monitoring indicated that ditches cut close to the road led to increased settlement by reducing the ability of the peat to act as a mat. In relation to the road that was the subject of the study, Barry *et al*. (1992) found that a track constructed from logs and stone was unable to maintain its surface elevation 0.5 metres above the surrounding ground (as had been originally specified) whilst a timber piled raft with a geogrid reinforced with a stone pavement was shown to perform satisfactorily.

3.15 One study (2+) investigated incremental controlled compression of the peat in advance of a housing development (Berry, 1983). He identified two options for loading peat and predicting settlement times but this was based on a field trial and not a pilot scheme.

3.16 A review of published experimental data (2+) that combined the authors' own data (Berry *et al*. 1972) found that settlement of amorphous granular and fibrous peat showed very close agreement with theoretical predictions. Reporting on a subsequent construction site study (2+) Berry *et al*. (1975) found agreement between observed and predicted rates of settlement. This same study found a decrease of around three orders of magnitude (ie a factor of a thousand) in vertical permeability during the consolidation process with a corresponding decrease in compressibility that had a net effect of reducing drainage rates. These authors also found that settlement times varied depending on the consolidation pressure.

3.17 A review (2++) of testing procedures for predicting settlement in peat by Hobbs (1986) concluded the following:

Water properties

- The bulk of the water within the peat is held as intracellular and inter-particle water with the proportions depending upon the structure and morphology of the plants present.
- Drainage of peat influences the proportions and quantity of water in the peat.
- There is considerable evidence that fibrous peats have a higher total water content than granular-amorphous peats.
- The stronger, less decomposed peat is more susceptible to compression than softer, more highly decomposed peat.

Engineering properties

- The permeability of the peat controls the rate of consolidation.
- The tensile strength of the acrotelm depends upon the plant cover. The acrotelm is more permeable than the catotelm but permeability declines with depth.
- The permeability of the catotelm depends on the botanical composition (Sphagnum moss tends to produce less permeable peat), the degree of humification, bulk density (higher bulk density = lower permeability), fibre content (higher fibre content = higher permeability), drainable void ratio/permeability (higher void ratio = higher permeability) and surface loading (diminishes the permeability by decreasing the void ratio/porosity).

Permeability under load

- Primary consolidation (ie the expulsion of pore water accompanied by structural re-arrangement of the particles) is a relatively short-term process.
- Secondary consolidation (or ‘secondary compression’), which is influenced by the size of the load, is the dominant process with the rate of settlement possibly increasing over time. This process is largely independent of the water content.

Overburden and pre-consolidation

- Drainage of mires increases the overburden pressure with the extent depending upon the drawdown and the age of the drainage scheme.
- Accurate prediction of the amount and progress of settlement is not possible.

3.18 One study (2+) quantified the consolidation of fibrous peat using a combination of laboratory analysis and existing published data (Mesri & Ajlouni, 2007). This study reported that fibrous peat particles are large and water-filled making them very compressible. They also found that on compression, the permeability of fibrous peats decreases dramatically.

3.19 Reporting (2+) on the construction of a metalled ‘floating’ road which was considered in the review as it also investigated settlement and settlement rates, Blackwood *et al*. (2006) noted that the route went over 4.3 metres (14 ft) of deep peat and that the settlement during primary consolidation of 0.6 metres (2 ft), was less than was calculated.

3.20 One study (2++) investigating the shear strength of peat found that shear behaviour was sensitive to over-consolidation (Cola & Cortellazzo, 2004).

3.21 A review (4+) of the current practices for construction of roads over peatlands in Northern Europe reported that the use of geotextile (for heavier trafficked roads) did not reduce the overall settlement in the long-term and that soil creep may affect the long-term performance of the geotextile (Munro, 2004).

3.22 An investigation (2+) into the effect of stress and temperature on secondary compression of peat found that a large fraction of the total settlement was due to secondary compression and that tests indicated that the rate of compression increases with time so that constant settlement predictions may underestimate the settlement (Fox & Edil, 1996).

3.23 An investigation (2++) into the impacts of road building and drainage upon peat structure found that changes in peat surface elevation can be related to changes in water level (Bradof, 1992). This study reported that on one site between 1915 and 1979/82, the average subsidence was c.3 mm per year and at a second site, over the same period, the average subsidence was c.10 mm per year. One of the sites showed a weak negative correlation between subsidence and distance from ditch (closer = greater subsidence).

3.24 A study (2+) of the construction techniques in relation to embankments reported that an increase in shear strength is found with decreasing water content (Casagrande, 1966).

3.25 A study (2++) into settlement rates in peat affected by construction (Lefebvre *et al*. 1984) reported that primary consolidation took between 10-20 days after construction and the inferred secondary consolidation in the field was about double that of the laboratory tests.

3.26 A study (2+) of the settlement rates of peat by Landva & Rochelle (1983) reported that Radforth peats (fibrous peats with little or no mineral matter) were highly compressible with a high rate of deformation and that as a result, predictions of magnitude and rate of settlement are difficult.

3.27 An investigation (2+) into the causes of a road failure on peat in Ireland (Hanrahan, 1964) found that variable settlement (deformation) of the road took place as a result of the non-uniform, and in places, excessively thick applications of gravel.

3.28 A study (2+) reporting the problems of constructing roads on peat noted that displacement of peat took place during loading despite the fill being added at a rate aimed at preventing displacement. This rate of application was too low for practical construction purposes. The behaviour of the peat under load appeared to be affected by the properties of the peat itself, which were not fully understood at the time of the research (Lake, 1961).

Peat stability

3.29 A review (4+) aimed at providing guidance on peat landslide hazard and risk assessments (Astron, 2006) identified the following most frequently reported anthropogenic (ie resulting from human activity or influence) factors for peat mass movements:

1) The alteration to drainage patterns focusing drainage and generating high pore-water pressures along pre-existing, or potential, rupture surfaces.
2) Unloading of the peat mass by cutting of peat at the toe of a slope reducing support to the upslope material.
3) Digging and tipping, which may undermine or load the peat mass respectively and may occur during building, engineering, farming or mining (including subsidence).
4) Changes in vegetation cover caused by burning, heavy grazing or stripping of the surface peat cover, which may reduce the tensile strength of the upper layers of the peat body.

3.30 One study (2++) investigating the causes of 9 peat slope failures in August 2008 in Ireland found that suspected trigger for one failure was the construction of a track (Dykes & Jennings, 2011; see Figures 2 and 3). Following a ’discussion’ on this paper in the journal of publication, Dykes & Jennings made the further observation in their reply that the cutting through of the peat to a depth of 1-1.5 metres as part of the process for extracting peat ‘turves’ destroyed the tensile strength of the peat at the site in question, thereby contributing to the occurrence of the slope failure when loaded by the construction work (Long *et al*., 2011).

3.31 A study (2++) investigating the causes of landslides on Cuilcagh Mountain in northwest Ireland found that of the 45 landslides investigated, one slide had a drainage ditch as a contributory factor (see paragraph 3.9) and another had a leaking pvc water pipe and the trench cut for the pipe as a contributory factor (Dykes *et al*., 2008).

3.32 A study (2++) investigating the tensile strength of peat and its relationship to specific blanket bog failures was able to quantify the importance of acrotelm tensile strength in the occurrence or not of bogflows (Dykes, 2008a).

3.33 A review (2++) of slope instability and mass movements by Dykes and Kirk (2006) identified that ditches across a sloping bog may eliminate down-slope support for the bog above the ditches (2 examples). They found that a common effect of drainage channels was the transfer of additional storm runoff into failure zones either directly or indirectly through connecting natural pipes (4 examples). Drainage associated with forestry ploughing was found to have contributed to one failure.

3.34 A study (2++) investigating the causes of slope failures at Dooncarton Mountain in Ireland found that 40 separate slides were recorded but that contrary to the previous cited paper (see paragraph 3.33) and other reports (for example, see paragraph 3.37, the same case referred to also in paragraphs 3.31 and 3.42), drainage channels cut across the slope at two of the landslides were not determined to have played a significant role in this case (Dykes & Warburton, 2008). These authors did find that cutting of peat for fuel on one site contributed to the instability.

3.35 An investigation (2++) of the role of peat liquidity in blanket bog failures by Yang & Dykes (2006) found that under certain conditions, the movement of water into pore spaces may lead to deformation of the peat. Where peat is susceptible to this, engineering works in the form of loading associated with wind farm construction or the storing of material on a peat body, can potentially lead to failure of the peat body.

3.36 A review (2+) of the evidence for a link between hill slope hydrology and mass movements in areas of blanket peat in the north of England found that out of 18 peat failures, 7 may have had an anthropogenic activity as a contributing factor (Warburton *et al*. 2004). A similar review (2++) by Dykes (2008b) on the causes of peat slope failures in Ireland found that around 50% were probably associated with anthropogenic influences.

3.37 A study (2++) into the causes of a specific slope failure on Cuilcagh Mountain in Ireland in 1998 concluded that the presence of a degraded drain and natural soil pipes contributed to the failure of the slope (Dykes & Kirk, 2001).

3.38 Investigating (2+) the mechanisms of peat failures in the North Pennines, Carling (1986) reported that slides occurred on slopes that had already displayed a history of mass movement and that the alignment of drainage channels may have contributed to instability of the slope.

3.39 A study (2+) of the causes of seven bog slides in Ireland found certain common factors: torrential rainfall, breaks of slope at the head of the movement, drains (4 slides) or streams and an impervious layer under the peat (Tomlinson & Gardiner, 1982).

3.40 A study (2+) into the causes of two peat slides in Ireland found that they were likely to have been caused by a combination heavy rainfall, degraded ditches and slope morphology (Wilson & Hegarty, 1993).

3.41 A review (4+) of issues around the Derrybrien bog slide (Lindsay & Bragg, 2005) reported that a smaller slide related to the construction of a turbine base and adjacent road also occurred prior to the main slide. They found that the site showed movement of peat that was not all related to the construction activity although some of it (for example, the bowing of a drain) clearly was. The authors also draw attention to another nearby wind farm where a peat landslide was observed and reported that that slide is believed to have also originated at an access road.

3.42 A review (2++) of the causes of peat slope failures in Ireland (Dykes, 2008b) concluded that:

1) Future weather patterns may make peatlands more susceptible to failure.
2) Old and degraded land drains and boundary ditches can focus water into a particular area of slope or reduce lateral support for the peat layer upslope from the ditch.
3) New wind farms are increasing the risk of future peat landslides as a result of the loading from ‘floating’ gravel access roads.

3.43 A summary report (4+) on the issues surrounding the construction of a 3 km access track across blanket bog highlighted several issues:

1) Material underlying the track was squeezed sideways and the adjacent bog rose.
2) Material underlying the track compressed due to the weight of the track and the track sank into the bog.
3) Most of the failures of the track were in the degraded cut-over bog and required considerable depths of stone to build the track, in some cases 1.3 metres rather than the design depth of 0.3 metres.
4) Surface flow drainage had been concentrated in places resulting in scouring.

Vehicle use on unmade tracks

3.44 One study (2++) found that between one and four passes with a high axle load (16 Mg) on well-decomposed sedge peat compacted the peat to a depth of 0.4-0.5 metres and this compaction persisted for at least three years (Alakukku, 1996a). Another study (2++) by the same author revisited plots 9 years after the intervention and found that all of the peaty soils in the study demonstrated compaction effects at the sub-soil level (below 0.25 metres) (Alakukku, 1996b).

3.45 A study (2++) of the mechanical properties of peat in relation to vehicle use found that in field situations, the bulk density of the peat, the mean stiffness (strength) of the surface mat and the stiffness of the underlying peat all increased when the peat was drained (Rahman *et al*. 2004).

Further research recommendations

3.46 We are confident in our conclusions as drawn from the available evidence, but most of the evidence relates to specific examples or to (geotechnical) experiments relating to particular engineering contexts. Hence although the general nature of some of the reported effects on peat are well known, the precise mechanisms and factors that may determine the magnitude and extent of those impacts – which may result in improved capabilities for predicting such effects – are uncertain if not unknown. Particular difficulties are experienced by engineers planning the construction of access tracks for wind farms or other management purposes because of insufficient knowledge of how peat strength relates to other peat properties and how it can be reliably measured, interpreted and used in quantitative stability assessments.

3.47 We have therefore identified several specific studies that would address critical knowledge gaps highlighted by the evidence:

1) Tracks are linear features in the landscape that will cross natural drainage directions and as such may present particular difficulties in terms of preventing negative effects on the peatland hydrology. The reduction of permeability that results from consolidation under a 'floating' constructed track (conclusion 1), or even arising from vehicles on the peat surface – both the process and the nature and extent of the effects of this process – are unknown. These issues would need to be investigated by means of long-term monitoring of a track (or tracks) following construction and with reference to pre-construction conditions.
2) A long-term investigation of the actual effects of constructing a typical 'floating' gravel road, as specified in 1 (above), would enable other, related issues to be examined in detail. These would include:

   - the biodiversity impacts arising from (a) altered downslope hydrological conditions and (b) the use of alkaline road gravel (limestone) on otherwise acidic peatland;
   - all other relevant hydrological properties of the peat mass including features such as pipes and desiccation cracks, and how they may affect the overall response of the peat; and
   - geotechnical properties of the peat mass, how they relate to the botanical composition of the peat and how they change under loading.

3) In parallel with 2)(3rd bullet point), above, further research is needed into the geotechnical properties of peat, how they relate to other peat properties and how they can be reliably measured and utilised in engineering design and stability assessments (particularly, but not exclusively, relating to planned construction of tracks, and supporting conclusions in points 2–4). These issues would need to be investigated by means of extensive field and laboratory measurements of peat, involving blanket bogs of varying botanical and environmental characteristics (for example, Ireland, Pennines, Shetland).
4) A component of the study suggested in 3 (above) would ideally also determine the nature of any changes in strength of the surface layers of the peat in response to drying (conclusion 2).

3.48 See Section 8 for further detail relating to research recommendations.

Photos: J. Gunn.

Figures 4 and 5 This small, non-mettalled ‘floating road' was built in around 1998 across blanket peat in the Cuilcagh Mountain Park, Co. Fermanagh, Northern Ireland. Although largely successful in terms of its purpose and design (in allowing vehicle access), evidence statement 3.43 in part refers to this example.

4 Do tracks (constructed or unmade) alter the hydrological system of blanket peat at either surface or sub-surface level?

4.1 The chapter summarizes the nature and strength of the evidence and identifies the conclusions reached based upon the evidence reviewed and recommendations for research in relation to this question

4.2 The distribution and movement of water through and over blanket peat depends on the hydrological characteristics of the peat system. The boundary between the acrotelm and the catotelm (see paragraphs 1.13-1.15 for definitions) is normally defined as the maximum depth to which the water table (ie the upper surface of the water saturation) may occasionally fall during particularly warm and dry periods of weather in summer, ie no more than about 0.5 m.

4.3 Under normal seasonal weather conditions many blanket bogs in the north and west of the British Isles tend to remain saturated to the surface all the time, although in England, seasonal variations in the water table depth have been recorded in the North Pennines. In general, this means that rainfall usually runs off rapidly over the surface of the bog because it cannot infiltrate into the already-saturated acrotelm (for example, Holden, 2011; Evans *et al*., 1999). Drainage of the peat would not normally be expected to reduce such overland flow because it may cause the peat to shrink, reducing the water content and also the total water storage capacity.

4.4 Even during a hot period in summer, when the water table has fallen below the surface, it may require only a small amount of rainfall to refill the available storage capacity before overland flow begins. This rapid surface runoff is an important and characteristic component of blanket bog hydrology.

4.5 In assessing the question above it has been necessary to include within the review any activity that results in the blanket peat having a reduced capacity to store water or a reduced capacity for water to flow freely across the peat surface.

Summary of evidence and conclusions

4.6 A body of strong evidence was relevant to this question with two 2++, one 2+, two 4+ publications specifically identifying roads or tracks as part of the study. Four 2++ and six 2+publications concerned the response of peatland to loading or the influence of drainage. It should be noted that the impact of drainage on blanket bog is covered in the review topic on restoration of blanket bog.

4.7 The consolidation processes that follow surface loading of peat, and the consequences for the peat in terms of drainage, as explained in paragraphs 1.13-1.15, are also directly relevant to this section of the report.

4.8 There is strong evidence that loading of peat (for example, by building or placing fill materials on it) results in settlement of the peat (Barry *et al*. 1992 [2+], Berry, 1983 [2+], Berry *et al*. 1972 [2+], Hobbs, 1986 [2++]) and a decrease in permeability of the peat (Berry *et al*. 1975 [2+], Mesri & Ajlouni, 2007 [2+], Hobbs, 1986 [2++], Ruseckas, 1998 [2+]). These changes can also affect the stability of the peat (See Section 3.29 - 3.43).

4.9 There is strong evidence that drainage of blanket peat results in the settlement of the peat (Bradof, 1992 [2++], Hobbs, 1986, [2++], Barden, 1968 [2+], Barry *et al*. 1992 [2+], Ruseckas, 1998 [2+]).

4.10 There is evidence that extent of the settlement of peat due to drainage depends on the age of the drainage scheme and the associated water table draw-down, making accurate prediction of the amount and progress of settlement impossible (Hobbs, 1986 [2++]).

4.11 There is weak evidence that roads constructed using a log raft with gravel top layer usually sink (Barry *et al*. 1992 [2+], Lindsay & Bragg, 2005 [4+]).

4.12 There is weak evidence that the fibrous peat found within the surface of a peat body is more compressible than the deeper amorphous peat (Mesri & Ajlouni, 2007 [2+], Hobbs, 1986 [2++]).

4.13 There is evidence that the strength of the acrotelm (surface peat) depends upon the plant cover (Hobbs, 1986 [2++]).

4.14 From this we have concluded that:

- Drainage of peat results in deformation (in the form of settlement) of the peat.
- Small, permanent (non-metalled) constructed tracks will result in settlement of peat[5].
- Constructed tracks result in the reduction of sub-surface flow through the peat because of the consolidation process.

4.15 There is evidence that the bulk of the water in peat is held as intracellular and inter-particle water with the proportions depending upon the structure and morphology of the plants present. Water is held in those spaces by capillary and adsorption forces (the remainder, a tiny fraction, draining freely from macropore spaces due to gravity) (Hobbs, 1986 [2++]).

4.16 There is evidence that drainage of peat influences the proportions and quantity of water in the peat. When the peat body settles (and settlement is not necessarily uniform) water is squeezed out from the intracellular and inter-particle spaces. An analogy would be toothpaste being squeezed out of a tube. The precise mechanisms are not scientifically known (Hobbs, 1986 [2++]).

4.17 There is weak evidence that drainage channels (with or without roads) can reduce surface saturation and, hence, overland flow (Lane & Milledge, 2012 [2++], Lindsay, 2007 [4+]).

4.18 There is moderate evidence that ditches can contribute to slope instability through directing water into failure zones (Dykes & Kirk, 2006 [2++]) or by removing downslope support (Dykes & Kirk, 2001 [2++]).

4.19 This leads us to conclude that:

- Whilst ditches play a role in managing runoff, on balance they are damaging to peat because they result in drying and possibly, through different mechanisms, instability of the peat. [If peat oxidises, it loses mass (and, in association with the concurrent drying, volume) and density, such that it may become locally buoyant. If excess rainwater can reach the base of such peat and raise pore water pressures sufficiently (and across a large enough area), instability may be promoted by the peat being floated off its base].

[5] It is recognized that there is a degree of duplication and overlap between the conclusions of Sections 3 and 4 as settlement affects structure and hydrology. This reflects the consistency and level of agreement within the evidence base.

- Compression of the peat through track construction may lead to accumulations of surface runoff water (ponding), which may lead to erosion and / or instability of the track and adjacent peat.

4.20 There is evidence from one study that recovery of blanket bog vegetation on unmade vehicle tracks following cessation of use was towards a grass-heath community rather than a blanket bog one and that recovery may not take place without further intervention (Charman & Pollard, 1995 [2++]).

4.21 From this we conclude that:

- That vehicle use on unmade tracks damages vegetation in ways that are not fully understood and may be irreversible without management intervention (the efficacy of which has not been assessed).

Analysis and evidence statements

4.22 The results of one study (2+) that proposed a simplified model for predicting primary and secondary consolidation of clay and peat agreed with other studies: Drainage results in deformation of the peat but the processes taking place were not necessarily agreed (Barden, 1968). This author also recognized that that drainage of micropores was a key process, but that at the time of writing, the physics was not yet established.

4.23 One study (2+), reported in paragraph 3.14 but also relevant here, identified that lowering of the water table was expected to cause settlement of the peat by three mechanisms:

- increase in (vertical) stress causing rapid settlement in permeable peat;
- drying shrinkage causing irreversible changes in the peat; and
- allowing aerobic conditions that result in an increased rate of decomposition (Barry *et al*., 1992).

4.24 These authors reported that field monitoring indicated that ditches cut close to the road led to increased settlement by reducing the ability of the peat to act as a mat.

4.25 These studies been have reported in paragraphs 3.15 and 3.16 respectively and involved the investigation of preloading of peat (Berry, 1983, 2+), (Berry *et al*., 1972, 2+), (Berry *et al*., 1975, 2+). Their results were consistent with previous studies with the additional finding of a decrease in vertical permeability of three orders of magnitude (ie a factor of a thousand) during consolidation, with a corresponding decrease in compressibility that had a net effect of reducing drainage rates. These authors also found that settlement times varied depending on the consolidation pressure.

4.26 One study (2++) found that drainage channels have the effect of re-arranging the surface drainage patterns of a slope, resulting in reductions in surface saturation (Lane & Milledge, 2012).

4.27 One study (2+) quantified the consolidation and compression of fibrous peat using a combination of laboratory analyses and existing published data (Mesri & Ajlouni, 2007). This study reported that fibrous peat particles are large and water-filled, making them very compressible. These authors also found that upon compression, the permeability of fibrous peats decreases dramatically.

4.28 One study (2+) on the changes to the physical and hydrological properties of peatland under forest, following drainage 30 years previously, found that the peat had settled by 15-25 cm in the middle of the drained area and by 24-37 cm near the ditches (Ruseckas, 1998). The same study found that the bulk density in the 0-20 cm depth zone was almost doubled (increased by a factor of 1.6-2.1) and that in the same horizon under a road, the hydraulic conductivity had been reduced by a factor of 60-150 times.

4.29 A study (2++) investigating the recovery of vegetation on blanket bogs following the cessation of track use found that blanket bog vegetation had a poorer recovery in comparison to other vegetation communities (Charman & Pollard, 1995) and concluded that neither of the two tracks with a blanket bog vegetation community saw a successful regeneration of bog vegetation This study found that with regard to the recovery of the blanket bog vegetation, the direction of succession was towards a grassland-heath community rather than the original blanket bog community. These authors suggested that the period of recovery for blanket bog on Dartmoor was 24 years and that natural restoration to an undamaged state may never take place in the absence of intervention.

4.30 A study (2++) investigating the impacts of road building and drainage on peat structure and vegetation found that diversion of the natural flow paths of water led to a lowering of the water table on one side of the road (Bradof, 1992). This author also found that changes in the water table depth resulted in changes in peat surface elevation.

4.31 One study (4+) commissioned to investigate issues around wind farm construction identified that road construction could disrupt the surface hydrology of peat sites amounting to several square kilometres in area (Lindsay, 2007). The author also identified that disruption of upslope water movement would depend in part on whether a drain is installed parallel to the upslope side of the road. In the absence of a drain, there is a tendency for water to pond along the upslope side of the road and this could contribute to slope instability. The author reported that cross-drains (drains running under the road) tended to be spaced at about 50 metre intervals meaning that only relatively small areas down slope would have water fed to them. The author noted that in the examples that were investigated, the management response to a road sinking and becoming flooded was often to install major drainage works.

4.32 One study (4+) commissioned to review issues around the Derrybrien bog slide (Lindsay & Bragg, 2005) noted that where floating roads used a timber raft, the raft eventually becomes waterlogged with the weight of the aggregate pushing it further into the peat. In periods of high rainfall, water from the now higher surrounding acrotelm drains into (and onto), the road. This in turn leads to an increased requirement for drainage which leads to exposure of peat and oxidative wastage. Where water is channelled under pressure, the force can lead to the removal of vegetation and initiate erosion.

4.33 An investigation (2++) of slope instability by Dykes and Kirk (2001) found that ditches across a sloping bog may eliminate lateral support for the bog upslope of any ditches. The same authors (2006) found that a common effect of drainage channels was the transfer of additional storm runoff into failure zones, either directly or indirectly through connecting natural pipes (4 examples). Drainage associated with forestry ploughing was found to have contributed to one failure.

4.34 Hobbs - note that this summary is found in Section 3.17.

Research recommendations

4.35 We are confident that our conclusions are correct but there are significant gaps in our understanding of the hydrological properties and behaviour of the peat and of ecological changes associated with the construction of tracks and, hence, restoration requirements. The research recommendations specified under Section 3.46 – 3.48 would enhance understanding and provide substantial additional quantitative evidence relating to Chapter 4. Issues related to the restoration of damaged peatlands will be examined in the report by the 'Peatland Restoration' panel. However, it is clear that evidence of recovery of peatland vegetation following damage relating to vehicle use on tracks or following removal of temporary constructed tracks, is extremely limited. A long-term monitoring investigation of the proximal and lateral effects on surficial hydrology, erosion and vegetation change at a variety of contrasting sites damaged by temporary constructed tracks or by vehicles on unmade tracks (then protected from further disturbance) would address the scientific uncertainties.

Photo: A. Crowle, 2007.

Figure 6 When this photograph was taken in the North Pennines, the track was about ten years old and this corner had been built up at least once. At the time of construction this track was above the surrounding bog

Photo: A.Crowle, 2007.

Figure 7 Ponding of water by the side of a moorland track in the North Pennines. Note the drainage channel intended to remove the surface water

5 Do type of vehicle and usage influence the impact of the track (constructed or unmade) upon either the structural integrity or hydrology of the blanket peat?

5.1 This chapter summarizes the nature and strength of the evidence and identifies the conclusion reached based upon the evidence reviewed and recommendations for research in relation to this question. It should be noted that the only evidence discovered related to unmade tracks.

Summary of evidence and conclusions

5.2 Seven studies (four 2++, two 2+, one 3+) reported on the effects of vehicle use on the structural integrity or hydrology of blanket peat.

5.3 There is moderate evidence that there is great variation in the inherent strength of peat and this variation determines the susceptibility of a given site to damage by vehicular movements (Arp & Simmons, 2012 [2++], Sparrow *et al*. 1978 [2++], Nugent *et al*. 2003 [2++] Wong *et al*. 1979 [2++]). Also, the wetter the peat, the more damage takes place (Sparrow *et al*. 1978 [2++], Robinson *et al*. 2006 [3+]).

5.4 There is moderate evidence that damage to the peat surface increases with the weight of the vehicle and the number of vehicle movements (Ahlstrand & Racine, 1993 [2++], Saarilahti, 1997, [2+]) as does soil compaction (Sparrow *et al*. 1978 [2++]).

5.5 There is weak evidence that the mode of movement, ie ‘caterpillar tracks’ or wheels, can have a bearing on the damage caused to the peat surface with tyres being reported as more damaging than rubber tracks (Wong *et al*. 1979 [2++]). Tyre ruts were found to re-direct drainage channels and, in one case, partially drained a quaking bog (Robinson *et al*. 2006 [3+]).

5.6 Trail braiding occurs when multiple tracks diverge from, and converge with, the original trail in areas which are less passable to vehicles or people on foot due to rutting and ponding of water. There is weak evidence that organic soils (including blanket peats) were found to be most susceptible to the development of braiding with an average of 8 semi-parallel tracks covering a width of 17-125 metres (Arp & Simmons, 2012 [2+]). The same study found that the most severely degraded trails were consistently found along the upslope edge of the trail.

5.7 There is moderate evidence that the increasingly repeated passage of vehicles over peat destroys the vegetation and damages the surface layer, resulting in the development of a quagmire (Sparrow *et al*. 1978 [2++], Ahlstrand & Racine 1993 [2++], Arp & Simmons, 2012 [2+]). As would be expected, the greater the number of vehicular movements, the greater the compression of vegetation tussocks and the greater the area of peat that is exposed.

5.8 From this we have concluded that:

- Damage to peat associated with unmade tracks depends on the peat type, the weight of vehicle, the number of vehicle movements and the type of tyre or 'caterpillar' track used by the vehicle.

Analysis and evidence statements

5.9 One study (2+), investigating both mineral and muskeg soils (see Glossary), reported that damage varied depending upon trail use, soil type and associated vegetation (Arp & Simmons, 2012. One study (2++), investigating peats less than 50 cm in depth and underlain by cobbles, reported that peat depth and drainage were the most important factors influencing the long-term impact of traffic on soil (Sparrow *et al*. 1978). Both of the previous two studies were concerned with off-road vehicles, but did not identify the types of vehicles. Another study (2++), based on a raised bog, reported that the vehicle influence was generally confined to the top 40 cm (Nugent *et al*. 2003) but this focused on forestry harvesting machines. As may be expected, a study (2++) by Ahlstrand & Racine (1993) found that heavier all-terrain vehicles usually produced deeper tracks than lighter vehicles (vehicles varied in weight between 100-1200 kg with tyre track widths ranging from 0.7-1.2 metres).

5.10 One study (2+) reporting 44 (least used) to 155 (most used) round-trip vehicle movements resulted in extensive braiding of trails on muskeg, with an average of 8 semi-parallel tracks covering a width of 17-125 metres. About 25% of the trail braids on muskeg soils were un-vegetated. These trails were characterised by the presence of ponded water in trail depressions resulting from a combination of erosion and freeze thawing. More severely degraded trails were consistently found along the upslope edge of the trail corridor (Arp & Simmons, 2012).

5.11 One study (2++) that was focused on forest harvesting machines (Nugent *et al.* 2003) found that on a raised bog, the initial strength of the surface peat significantly influenced rut development. A study (2++) looking at vehicle movements on peat reported that the underlying peat deposit had a much lower bearing capacity and shear strength than the surface mat (Wong *et al*. 1979). This same study found that rubber tyres created deeper ruts than similar vehicles mounted on continuous rubber 'caterpillar' tracks. They concluded that rubber tracks or tracks with rubber pads could offer a reasonable compromise with regard to traction requirements whilst minimising surface damage. Another study (2+) focused on machinery for forest harvesting (Saarilahti, 1997) reported that rut depth was related to the shear strength and/or penetration resistance of the soil and the wheel load combined with wheel dimensions. One study (2++) found that the wettest areas were often the most disturbed parts of a trail when subjected to heavy use (>12 vehicles a year) (Sparrow *et al*. 1978). The same study found that repeated off-road vehicle use destroyed the peat surface layer or mat, which became saturated and turned into a quagmire. One report (3+) found that erosion of the wettest ground, following off-road use, was one of the most damaging features (Robinson *et al*. 2006). The same authors noted that tyre-ruts re-directed small drainage channels and, in one case, partially drained a quaking bog.

5.12 One study (2++) found that peat compaction was significant along moderately and heavily used trails (6-12 and >12 vehicles per year respectively) but not along lightly used trails (1-6 vehicles per year) (Sparrow *et al*. 1978). The same study found that heavily used trails were completely denuded, whilst on less frequently used trails tall shrubs were the most injured plants. Sedges appeared to be the least susceptible plants to injury. Another study (2++) found that shrub injury rates were greatest during the first few passes by an all-terrain vehicle (Ahlstrand & Racine 1993). This study also found that the degree of sedge tussock compression and the amount of peat soil that became exposed along all-terrain vehicle trails increased in relation to vehicle weight.

Research recommendations

5.13 Whilst we are confident of our conclusion that vehicle use on unmade tracks is damaging, there remain significant gaps in our understanding. There are two types of study that could provide a meaningful body of knowledge and, thus, evidence relating to sub-question 3.

1) Long-term monitoring of the surface and subsurface peat properties and conditions following disturbance by vehicles driving across the peat and with reference to pre-construction conditions. This study would be directly comparable with recommendation 1 of sub-question 1, and would ideally be combined with the recommendation for sub-question 2.
2) A controlled experiment would ideally be undertaken in which different types of vehicles would be driven across designated strips of peatland repeatedly, with monitoring and analysis of peat surface conditions being undertaken repeatedly as the number of vehicle passes increases. Such a study would ideally be undertaken as the set-up for recommendation 1 (above) and would provide support for conclusion 1.
3) Recommendation 1 for sub-question 1 (post-construction monitoring of a constructed track and the peat beneath) could be enhanced by incorporating vehicle movements over the track. This would efficiently address conclusion 2, but it may be better to have a separate part of a monitored track for this purpose.

Source of data: **www.bv206.co.uk**. Photo: A. Crowle, 2009.

Figure 8 An example of track widening (braiding) in the North Pennines. The vehicle used in this example was hagglund which is a tracked vehicle (Gross vehicle weight 4,800 kg, ground pressure 140 k Pa (0.14 kp/cm^2))

Photo: D. Mitchell, 2012.

Figure 9 Damage caused by a hagglund in the North Pennines

6 Do tracks (constructed or unmade) lead to enhanced erosion of blanket peat?

6.1 Particulate Organic Carbon (POC) and Dissolved Organic Carbon (DOC) are derived from the peat mass itself and are physical manifestations that erosion processes are taking place. This chapter summarizes the nature and strength of the evidence and identifies the conclusions reached based upon the evidence reviewed and recommendations for research in relation to this question.

Summary of evidence and conclusions

6.2 No studies were found that related solely to constructed tracks and enhanced erosion on blanket peat. One study (2++) recorded the release of carbon and sediment during the construction of a wind farm which included road construction. One study (2++) recorded the release of carbon and sediment on unmade tracks created by researchers.

6.3 There is evidence from a single study that footpaths (unmade tracks) on peat lead to the loss of vegetation and a reduction in plant species richness. Sphagnum moss cover was the lowest on the most recently used path. Vascular plants were slower to recover than Sphagnum moss (Robroek *et al*., 2010 [2++]).

6.4 There is evidence from a single study that the absence of vegetation cover on the unmade track led to an increase in the number of runoff events by which POC (carbon particles that are too big to be filtered) was lost from the track. The mean concentration of POC was significantly higher in the track that had been used most recently although the concentrations in surface runoff declined as Sphagnum cover increased (Robroek *et al*., 2010 [2++]).

6.5 There is evidence from a single study that over the period of the study (one year), the mean DOC (carbon particles that can be filtered) did not vary significantly between unmade tracks (Robroek *et al*., 2010 [2++]).

6.6 There is evidence from a single study that bulk density, which indicates the level of peat compression, was not affected by unmade track use (Robroek *et al*., 2010 [2++]).

6.7 There is evidence from a single study that the construction of a wind farm which included roads resulted in the significant increase in the loss of DOC from the site. There was no evidence that the concentration of DOC decreased over time. High levels of sediment continued to be recorded even after the construction activities had ceased. This was thought to reflect inadequate provision for the trapping of silt on the site (Grieve & Gilvear, 2008 [2++]).

6.8 From this we conclude that:

- The disruption of peat by tracks at either a surface or sub-surface level results in erosion and this erosion is on-going.
- We have not been able to quantify levels of erosion derived from a constructed track as there is no research that has addressed this subject in isolation.

Analysis and evidence statements

6.9 One study (2++), investigating the impact of researchers walking upon unmade tracks on blanket bogs, found that track use clearly impacted upon the vascular plant community; this resulted in a lowering of species richness with a slower recovery of vascular plants compared with Sphagnum (Robroek *et al*., 2010). This study found that Sphagnum moss cover was affected by track type and was lowest on the most recently used track, although track type did not significantly affect non-Sphagnum mosses. These researchers also found that the most recently abandoned track had the highest bare peat cover and that the absence of vegetation resulted in a significant increase in the number of runoff events.

6.10 In relation to the carbon interactions arising from the use of unmade tracks by researchers, Robroek *et al*. (2010) found that over the period of study, mean DOC concentrations were not significantly different between tracks, whilst mean POC concentrations in the surface water of the most recently used track were significantly higher than the other two. The researchers also found that POC concentrations in the surface runoff decreased with increasing Sphagnum.

6.11 One study (2++) investigated the immediate impacts of the construction of a wind farm upon the fluxes of DOC (Grieve & Gilvear, 2008). This study did not separate the impacts of the track construction from the turbine base construction. The authors found significantly increased concentrations of DOC and sediment draining from the wind farm site. They found that even after the construction activities had ceased, the suspended sediment losses continued to be significantly elevated, which they explained in terms of a combination of fine silt washing into and from the track network, and ineffective provision for trapping sediment. The same study found that there was no evidence that the differences in DOC concentrations between the site and a control catchment decreased over time.

Research recommendations

6.12 There is a need to be able to quantify the amount and duration of erosion associated with constructed and unmade tracks on blanket peat:

- For unmade tracks, an appropriate study could be relatively easily established in conjunction with recommendations 1 and 2 of sub-question 3 by adding a detailed monitoring programme to establish amounts and rates of loss of vegetation cover, POC and DOC. However, it could also be done as a stand-alone study, ideally using an enhanced version of Robroek *et al*.'s (2010) methodology that includes vehicle tracks as well as footpaths.
- Erosion from, or associated with, constructed tracks should be explicitly investigated in conjunction with a new wind farm project, in association with the client and developer. This would enable a nested monitoring scheme focusing on varying lengths of road in varying topographic contexts (for example, planar slope, crossing drainage line) as well as (sub)catchment scale impacts or roads and ideally roads+turbine sites. This would provide knowledge of the primary sources of different types of sediment as well as the amounts and rates of erosion.
- An alternative to the previous recommendation would be to add detailed erosion monitoring to the detailed investigation of a designated research road, ie in conjunction with recommendation 1 of sub-question 1, although the conclusions would be limited compared with monitoring of an entire wind farm road network.

7 Concluding remarks and summary

7.1 The Tracks Review Group has considered the evidence and made the conclusions reported. This section summarises our findings in relation to the over-arching question. Also included within this section are our observations on wider issues that emerged from some of the evidence considered during this review.

7.2 The evidence presented in this Review has focused mainly upon the impacts of tracks and vehicle use upon blanket peat structure and hydrology with some studies looking at the impacts upon vegetation. We have found no studies of the impacts of tracks or vehicles upon the wider biodiversity of blanket peat or upon the associated ecosystem services.

7.3 The impact of tracks upon landscape was not reviewed. Images supplied by Peart (2012) and United Utilities (2012) indicate that in some cases this may require consideration.

7.4 The Review group noted that the impact of tracks was less well studied than other interventions in the uplands because it has only become a significant issue in recent years as demands on the upland environment, and the services it provides, have intensified.

7.5 The Review Group makes the following conclusions on the impacts of tracks upon the integrity and function of blanket peat based upon the evidence and wider issues identified in this document:

- Building upon peat compresses the peat and alters the drainage patterns on and around the peat, both within the peat body and over its surface. The level of compression and disruption depends upon the structure and wetness of the peat in question.
- Drainage of peat results in the settlement of the peat which disrupts the hydrology of the peat both within the peat body and over its surface.
- Drainage channels are damaging as they result in drying of the peat and may lead to instability of the peat depending upon their position within the slope or by channelling water into areas of structural weakness.
- Vehicle use on unmade tracks is damaging to the surface vegetation. The level of damage depends upon the type of vehicle and its weight, the number of journeys made and the wetness of the peat in question.
- The disruption of peat by tracks at either a surface or sub-surface initiates continuous erosion.

7.6 It should be noted that the impact of drainage upon blanket bogs is covered in the Evidence Review on blanket bog restoration. The Review Group felt it necessary to include within this review any activity that results in the blanket peat having a reduced capacity to store water or a reduced capacity for water to flow freely across the peat surface.

7.7 It is clear from the evidence considered within this review that peat is widely recognised as a challenging substrate from an engineering perspective. During the assessment of evidence it became apparent that there were several publications that are not intervention studies yet are relevant to the issue of construction of tracks upon peat: Countryside Commission for Scotland (1978), Land Use Consultants (2005), MacCulloch (2006), and Stoneman (1997). These could not be assessed formally. It would appear, however, from these publications that there is a good deal of experience of the construction techniques in relation to building tracks, but there was no evidence presented to support the methods being proposed. As a result, these publications were not included within the Review. A consistent theme throughout these publications is the requirement for some element of drainage as part of track construction. With respect to developing the evidence base there may be value in collating and gathering information drawn from well documented practice.

7.8 A recent development for vehicle use is an artificial membrane that is laid over the surface of the ground (for example, Figure 10). The use of this material on blanket bog is currently the subject of a research studentship based at Moor House National Nature Reserve and a neighbouring site and is due to report in 2015. This type of material may provide an important alternative to allowing access without the damage associated with unmade tracks, the hard engineering required for constructed tracks or indeed a hybrid solution where membranes might be used to reinforce sections of an unmade track, thus minimising the amount of work and cost associated with forming a track.

Photos: A Crowle, 2011 above, 2009 below.

Figure 10 Above: A mesh track surface in the North Pennines. Below: The same track prior to putting the mesh surface in place

8 Summary of research recommendations

8.1 These recommendations provide more detail than those presented within the main body of the report and are intended to be complementary.

Sub-question 1: Do tracks alter the structural integrity of blanket peat?

- Investigation of the variability of compaction impacts on the water storage capacity and permeability of peat.
- Development of techniques to measure peat strength and related properties, including how load is transmitted through the peat mass, to facilitate determination of the variability in these properties around the UK and how they may alter over time due to climate change.
- How excavation and construction of tracks affect peat stability and failure processes.
- Investigation of pre-loading techniques and calculations for blanket bogs during construction of upland tracks and whether pre-loading makes a difference in terms of impacts of tracks upon blanket bogs.
- The influence of water chemistry on the liquid limit and other geotechnical properties of peat.
- Specific research into tracks, their impacts and best practice for construction with regard to use on blanket peat.
- Effects of temperature (and loading) on settlement rates in blanket bog.
- Identification of slopes with characteristics that suggest they are susceptible to movement.

Sub-question 2: Do tracks alter the hydrological system of blanket peat at either surface of sub-surface level?

- The micro-scale hydrological processes within peat, particularly in response to loading and associated consolidation, and the field validation of loading effects predicted from laboratory results.
- Spatial and temporal patterns of runoff in, on and around tracks.
- Investigations into the impacts of different types of track and ditch construction on the hydrology of blanket peat and the role of ditches in creating instability in peat.
- The effects of pre-loading of blanket peat as a construction strategy for new tracks.
- Settlement rates of tracks on blanket bog and the associated impacts on hydrology.

Sub-question 3: Do type of vehicle and usage influence the impact of the track upon either the structural integrity or hydrology of the blanket peat?

- Long-term study to determine the extent of hydro-geomorphic processes and impacts on streamflow, water quality and aquatic habitats as a result of vehicle use around watersheds or on blanket bog.
- Quantification of the nature and extent of changes to drainage systems on blanket bog following vehicle use and recovery rates of mire/flush vegetation post-damage.
- Establish whether altered drainage systems recover naturally?
- Investigate whether there is a threshold for vehicle use on blanket bogs and if so, how to assess it?
- Quantify the impact of tracked vs wheeled vehicles on blanket peat vegetation, hydrology and structure and the nature and extent of rutting.

Sub-question 4: Do tracks lead to enhanced erosion of blanket peat?

- The spatial and temporal distribution of erosion and types of erosion, in relation to the type of track (ie constructed or unmade).

9 Glossary of terms

This glossary is set out to provide definition to terminology used in this report.

Term	
Acrotelm	The thin aerobic zone at the surface of the mire, underlain by the thick anaerobic zone called the catotelm. Literally 'top of marsh' and 'bottom of marsh', respectively, from the Greek (Hobbs, 1986; after Gore, 1983).
Bare peat	Term used to describe areas of exposed peat.
Blanket peat (aka) Blanket (bog) peat	Peat deposits formed by blanket bogs, ie bogs that grow outwards from initial accumulation sites (for example, topographic depressions) to cover the (mineral) land surface like a blanket.
Bog	A mire or peatland that derives all its water and nutrients from precipitation (ie rain, snow or mist).
Bog burst / bogflow / bog slide / peat slide / peaty-debris slide / peat flow	Types of peat landslides, historically used interchangeably but more recently explicitly defined (Dykes and Warburton, 2007). See landslide.
Catotelm	See acrotelm.
Compression / consolidation	Often used interchangeably to refer to the process of adjustment of a soil (or peat) to the application of a vertical load, involving expulsion of water from pore spaces and structural rearrangement of particles (including fibres) into a more densely packed arrangement. Strictly, compression is a short-term effect in which the loading and associated changes are transient, and the soil (or peat) recovers its original state after the load is removed, and consolidation is a long-term, slow ongoing process leading to effectively permanent change (Selby, 1993).
Compressive strength	Measure of the resistance to a vertical compressive load.
Diplotelmic (of active peat-forming bogs)	Having a two-layered structure comprising an acrotelm and a catotelm.
Hagg	(Swedish) natural gully in a bog.
Humification	Degree of decomposition of the plant material that constitutes the peat.
Hydraulic conductivity	A measure of the ease with which soil pores permit water movement through the soil, also known as the coefficient of permeability. It is the rate of flow of water per unit area of soil when under a unit hydraulic gradient. If the soil (or peat) is saturated, the hydraulic conductivity is equivalent to permeability (Selby, 1993).
Interventions	In the context of this Review, interventions are treatments that have been applied in any individual study, for example, the number of times a vehicle passed over an experimental area or the varying degrees of compression on a peat sample in a laboratory test.
Landslide / slope failure / mass movement	Downhill movement of soil, rock, peat or any other geological material as a result of the downslope gravitational force exceeding the minimum available (shear) strength of the materials on the slope.

Table continued…

Term	
Liquid limit	The water content at which the behaviour of a material in response to stress changes from being plastic to liquid in character. This is one of the Atterberg Limits, ie index (indicator) properies of soils determined using precisely definied standard tests.
Macropores	Pore spaces large enough that gravity drainage will dominate water movement, commonly taken as >0.06 mm diameter. See pipes.
Meta-analysis	Methods and techniques for comparing and contrasting the results from different studies with the aim of identifying patterns of similarity or differences.
Micropores	Pore spaces in which water will be retained by small-scale forces against the pull of gravity.
Mire	A wetland that supports peat-forming vegetation. Some authors use this term to include wetlands on mineral soils. See also bog and fen.
Moorland	A term use to describe unenclosed upland areas dominated by a range of semi-natural vegetation types. Not synonymous with peatlands.
Muskeg	Canadian Indian word for organic terrain, mire and peat (Hobbs, 1986; after Gore, 1983).
Oligotrophic	Mineral-poor.
Ombrogenous	(peat or vegetation) formed under ombrotrophic conditions.
Ombrophilous	(vegetation) tolerating a predominantly rainwater influence.
Ombrotrophic	(supply of nutrients) exclusively from precipitation thereby producing oligotrophic conditions.
Peat	Decomposing remains of dead plants and soil organisms that have accumulated in, or across, favourable parts of the landscape in terms of the availability of excess water to maintain saturation (waterlogging).
Peat deposit	Any accumulation of peat, for example, blanket bog, raised bog, etc.; also a term used specifically by the British Geological Survey to mean a peat body at least 1 metre thick.
Peat soil	In the UK soil classification system, a type of soil which includes all organic-rich soils.
Permeability	See hydraulic conductivity.
Pipes	Natural subsurface conduits analagous to cave passages in limestone. Hydrologically they behave as macropores, but a few can be large enough in places for a person to enter.
Pores	The spaces, or voids, between solid particles within a soil (or peat) that can contain air and/or water. Definitions and effects of hydrological processes are complicated in peat because some water is held within plant cells (ie conceptually the ‘solid’ particles) in Sphagnum-dominated peat.

Table continued…

Term	
Porosity	The proportion of the total soil (or peat) volume that comprises pore spaces.
Primary consolidation	Term used in peat engineering (Hobbs, 1986) to describe the initial stage of rapid drainage in response to the applied load.
Radforth peat	A term used in North America (primarily Canada) to refer to peat of low or insignificant mineral content consisting of mostly fibrous material (stems, leaves, fibers, root threads, rhizoids, etc.).
Runoff	The proportion of rainwater that is unable to infiltrate into the soil (or peat) and is instead transferred quickly towards drainage channels as 'free gravity flow' (ie over the surface or through subsurface pipes and other larger macropores). It also includes rapid downslope flow through the highly permeable uppermost layer of the soil (or peat), if there is any.
Saturation	All of the pore spaces being full of water. A saturated soil (or peat) cannot contain any additional water. This may refer to a specific limited zone within a soil (or peat), for example, below the water table.
Strength	Ability of a material (for example, peat) to resist deformation by compressive, shear or tensile stresses.
Shear strength	Measure of the resistance to a shear stress, ie opposing lateral stresses such as when trying to slide a pie off a baking tray (the friction between the base of the pie and the tray provides the shear strength in this example).
Tensile strength	Measure of the resistance to a tensile stress, ie a 'pulling' force such as experienced by the middle of the rope in a tug-of-war.
Secondary consolidation	Term used in peat engineering (Hobbs, 1986) to describe the subsequent long-term slow structural rearrangement of particles with further expulsion of water from micropores and from within plant cells.
Raised bog	Accumulation of peat on a lowland floodplain or in a shallow topographic basin that eventually grows higher than the influence of any surface runoff or groundwater so as to be entirely maintained by the excess of precipitation over evapotranspiration. This rainwater-fed upper part of the deposit comprises ombrotrophic bog peat.
RCT (Randomised Control Trial)	From clinical studies, where the selected subjects of a study are randomly allocated one of the treatments (including a zero treatment or 'control' option).
Voids	Small cavities in the soil, occupied by air or water or both.
Waterlogging	Permanent or prolonged temporary saturation of the ground resulting from high precipitation and poor drainage, or a more or less constant supply of groundwater and/or surface runoff.
Water table	the upper surface of a zone of saturation in the ground (for example, within a peat deposit).

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Appendix 1 Summary of studies by review question, study type, quality and location

Table A Summary of studies by review question, study type, quality and location

Do tracks alter the structural integrity of blanket peat?	Category & quality	Location of study
Publications relating to peat consolidation		
Alakukku (2 papers) investigated compaction by vehicle movements after 3 and 9 years respectively.		
Alakukku, L. 1996a & b.	2++	Finland
Barden proposed a simplified model for predicting primary and secondary consolidation of clay and peat.		
Barden, L. 1968.	2+	Great Britain
Barry *et al.* proposed a road construction method that was subject to specific environmental constraints.		
Barry, A .J, Brady, M.A. & Younger, J. S. 1992.	2+	Sumatra
Berry carried out a brief review of consolidation theory on peat and developed calculations of preloading times and weights on peat to be used for housing development.		
Berry, P. L. 1983.	2++	Great Britain
Berry & Poskitt reviewed published data and along with inclusion of their own data proposed a method of engineering assessment in the field of the consolidation of peat.		
Berry, P. L. & Poskitt, T. J. 1972.	2+	Great Britain
Berry & Vickers reviewed and tested the theory of consolidation of fibrous peat.		
Berry, P. L. & Vickers, B. 1975.	2+	Great Britain
Mesri & Ajlouni offered a quantification of consolidation and compression of fibrous peats.		
Mesri, G. & Ajlouni, M. 2007.	2+	North America
Blackwood and Vulova reported on the construction of a metalled "floating" road.		
Blackwood, T. W. & Vulova, C.V. 2006.	2+	North America
Munro reported on the current practices for construction over peatlands in Northern Europe.		
Munro, R. 2004.	4+	Scandinavia
Fox & Edil investigated the effect of stress and temperature on secondary compression of peat.		

Table continued…

Do tracks alter the structural integrity of blanket peat?	**Category & quality**	**Location of study**
Fox, P. J. & Edil, T. B. 1996.	2+	North America
Bradof investigated the impacts of road building and drainage upon peat structure and vegetation.		
Bradof, K.L. 1992.	2++	North America
Hobbs reviewed testing procedures for predicting settlement in peat.		
Hobbs, N.B. 1986.	2++	Great Britain
Lefebvre *et al.* investigated settlement rates in peat under construction.		
Lefebvre, G., Langlois, P., Lupien, C. & Lavallee, J.-G. 1984.	2++	North America
Landva & Rochelle studied the settlement of peat.		
Landva, A.O. and La Rochelle, P. 1983.	2+	North America
Casagrande investigated construction techniques in relation to embankments on peat.		
Casagrande, L. 1966.	2+	North America
Rahman *et al.* studied the mechanical properties of peat in relation to vehicle use.		
Rahman, A., Yahya, A., Zodaidie, M., Ahmad, D, Ishak, A & Kheiralla, A.F. 2004.	2++	Malaysia
Lake investigated the problems of constructing roads on peat.		
Lake, J. R. 1961.	2+	Great Britain
Gunn reported on the issues around the construction of a 3km track on blanket bog.		
Gunn, J. 1998.	4+	Ireland
Publications relating to peat stability		
Dykes and Jennings investigated causes of peat slope failures and mass movements in Ireland in August 2008. They also published a reply to a response to their paper.		
Dykes, A. P. & Jennings, P. 2011.	2++	Ireland
Dykes & Warburton investigated causes of peat slope failures at Dooncarton.		
Dykes, A. P. & Warburton, J. 2008.	2++	Ireland
Dykes *et al*. investigated causes of landslides on Cuilcagh Mountain.		
Dykes, A. P., Gunn, J., Convery. 2008.	2++	Ireland
Dykes investigated tensile strength of peat and its relationship to specific blanket bog failures.		
Dykes, A. P. 2008a.	2++	Ireland
Dykes & Kirk reviewed slope instability and mass movements.		
Dykes, A. P. & Kirk, K.J. 2006.	2++	Ireland
Yang & Dykes investigated the procedure for determining the liquid limit as an index property that may explain some peat failures.		

Table continued…

Do tracks alter the structural integrity of blanket peat?	Category & quality	Location of study
Yang, J. & Dykes, A. P. 2006.	2++	Ireland
Cola & Cortellazzo established the shear strength of two peat soils.		
Cola, S. & Cortellazzo, G. 2005.	2++	Italy
Warburton *et al*. reviewed the evidence for a link between hillslope hydrology and mass movements in areas of blanket peat.		
Warburton, J., Holden, J. & Mills, A. J. 2004.	2+	Great Britain
Dykes & Kirk examined the role of drainage and pipes in a peat slide the trigger of the slide.	2++	Ireland
Carling investigated mechanisms of peat failures in the North Pennines.	2+	Great Britain
Tomlinson & Gardiner investigated causes of bog slides.		
Tomlinson, R.W. & Gardiner, T. 1982.	2+	Ireland
Hanrahan investigated causes of a road failure on peat.		
Hanrahan, E.T. 1964.	2+	Ireland
Wilson & Hegarty investigated causes of peat slides.		
Wilson, P. & Hegarty, C. 1993.	2+	Ireland
Lindsay & Bragg reviewed issues around the Derrybrien peat slide.		
Lindsay, R, & Bragg, O. 2005.	4+	Ireland
Dykes reviewed the causes of peat slope failure.		
Dykes, A. P. 2008b.	2++	Ireland
Astron provided guidance on peat landslide hazard and risk assessments.		
Astron, 2006.	4+	Great Britain

Do tracks alter the hydrological system of blanket peat at either surface or sub-surface level?	Category & quality	Location of study
Barry *et al.* proposed a road construction method that was subject to specific environmental constraints.		
Barry, A .J., Brady, M.A. & Younger, J. S. 1992.	2+	Sumatra
Ruseckas investigated the changes to water-physical properties in a peatland under forest following drainage.		
Ruseckas, J. 1998.	2+	Russia
Charman & Pollard investigated the recovery of vegetation after vehicle track abandonment.		
Charman, D. J. & Pollard, A. J.1995.	2++	Great Britain
Bradof investigated the impacts of road building and drainage upon peat structure and vegetation.		
Bradof, K.L. 1992.	2++	North America
Lindsay & Bragg reviewed issues around the Derrybrien peat slide.		
Lindsay, R, & Bragg, O. 2005.	4+	Ireland
Publications relating to drainage		
Lane & Milledge investigated the impacts of upland drains on run-off generation.		
Lane, S. N. & Milledge, D. G. 2012.	2++	Great Britain
Lindsay investigated issues around wind farm construction.		
Lindsay, R. 2007.	4+	Ireland
Dykes & Kirk reviewed slope instability and mass movements.		
Dykes, A. P. & Kirk, K.J. 2006.	2++	Ireland
Dykes & Kirk reviewed slope instability and the role of a drainage ditch.		
Dykes, A. P. & Kirk, K. J. 2001.	2++	Ireland
Publications relating to the consolidation of peat		
Barden proposed a simplified model for predicting primary and secondary consolidation of clay and peat.		
Barden, L. 1968.	2+	Great Britain
Berry carried out a brief review of consolidation theory on peat and developed calculations of preloading times and weights on peat to be used for housing development.		
Berry, P. L. 1983.	2++	Great Britain
Berry & Poskitt reviewed published data and along with inclusion of their own data proposed a method of engineering assessment in the field of the consolidation of peat.		
Berry, P. L. & Poskitt, T. J. 1972.	2+	Great Britain
Berry & Vickers reviewed and tested the theory of consolidation of fibrous peat.		
Berry, P. L. & Vickers, B. 1975.	2+	Great Britain

Table continued…

Do tracks alter the hydrological system of blanket peat at either surface or sub-surface level?	Category & quality	Location of study
Hobbs reviewed testing procedures for predicting settlement in peat.		
Hobbs, N.B. 1986.	2++	Great Britain
Mesri & Ajlouni offered a quantification of consolidation and compression of fibrous peats.		
Mesri, G. & Ajlouni, M. 2007.	2+	North America

Do type of vehicle and usage influence the impact of the track upon either the structural integrity or hydrology of the blanket peat?	**Category & quality**	**Location of study**
Arp & Simmons assessed impacts of off-road vehicles on watershed processes.		
Arp, C.D. & Simmons, T. 2012.	2+	North America
Robinson *et al.* reported on the damage caused by motorcycles and quad-bikes.		
Robinson, L. M., Corner, R. D. & Roberts, F. J. 2006.	3+	Great Britain
Nugent *et al.* aimed to quantify the levels of peat compaction and surface rutting due to excessive passes by typical wood harvesting and extraction machines establish threshold limits for use of machine traffic.		
Nugent, C., Kanali, C., Owende, M.O., Nieuwenhuis, M. & Ward, S. 2003.	2++	Ireland
Wong *et al.* developed a model for characterizing muskeg properties in relation to vehicle use.		
Wong, J.Y., Garber, M., Radforth, J. R. & Dowell, J. T. 1979.	2+	North America
Sparrow *et al.* made assessments of the impacts of off-road vehicles on soils (mineral and peat) and vegetation.		
Sparrow, S. D., Wooding, F. J. & Whiting, E. H. 1978.	2++	North America
Ahlstrand & Racine investigated the response of vegetation to off-road vehicle use.		
Ahlstrand, G. M. & Racine, C. H. 1993.	2++	North America
Saarilahti investigated rut formation on peat as a result of forest harvesting.		
Saarilahti, M. 1997.	2+	Finland

Do tracks lead to enhanced erosion of blanket peat?	Category & quality	Location of study
Grieve & Gilvear investigated the impacts of disturbance due to construction a wind farm on the fluxes of dissolved organic carbon and suspended sediment in streams during the immediate post construction phase.		
Grieve, I. & Gilvear, D. (2008).	2++	Great Britain
Robroek *et al.* investigated the impact of tracks upon blanket peat vegetation and hydrochemistry.		
Robroek, B. J. M, Smart, R. P. & Holden, J. 2010.	2++	Great Britain

Appendix 2 Full citation list for publications included within the review

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Alakukku, L. 1996b. Persistence of soil compaction due to high axle load II. Long-term effects on the properties of fine-textured and organic soils. *Soil & Tillage Research*, 37, 223-238.

Ahlstrand, G. M. & Racine, C. H. 1993. Response of an Alaska, USA, Shrub-tussock community to selected all-terrain vehicle use. *Arctic and Alpine Research*, 25, 142-149.

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Astron. 2006. Peat landslide hazard and risk assessments best practice guide for proposed electricity generation developments. Edinburgh, Scottish Executive.

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Blackwood, T. W. & Vulova, C.V. Geogrid reinforced embankment constructed over peat soils in Clark County, Washington: Design and field performance. *Proceedings of the Airfield and Highway Pavement*, 317-328.

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Dykes, A. P., Gunn, J., Convery. 2008. Landslides in blanket peat on Cuilcagh Mountain, northwest Ireland. *Geomorphology*, 102, 325 -340.

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Appendix 3 Additional photographs

Plate A Mountain bike and foot path damage in the West Pennines. Photo: United Utilities.

Plate B Vehicle damage in the West Pennines. Photo: United Utilities.

Plate C An example of track damage submitted to the Uplands Evidence Review. Photo: A. Peart, 2008.

Plate D An example of track damage submitted to the Uplands Evidence Review. Photo: A. Peart, 2007.

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